REFLECTIONS

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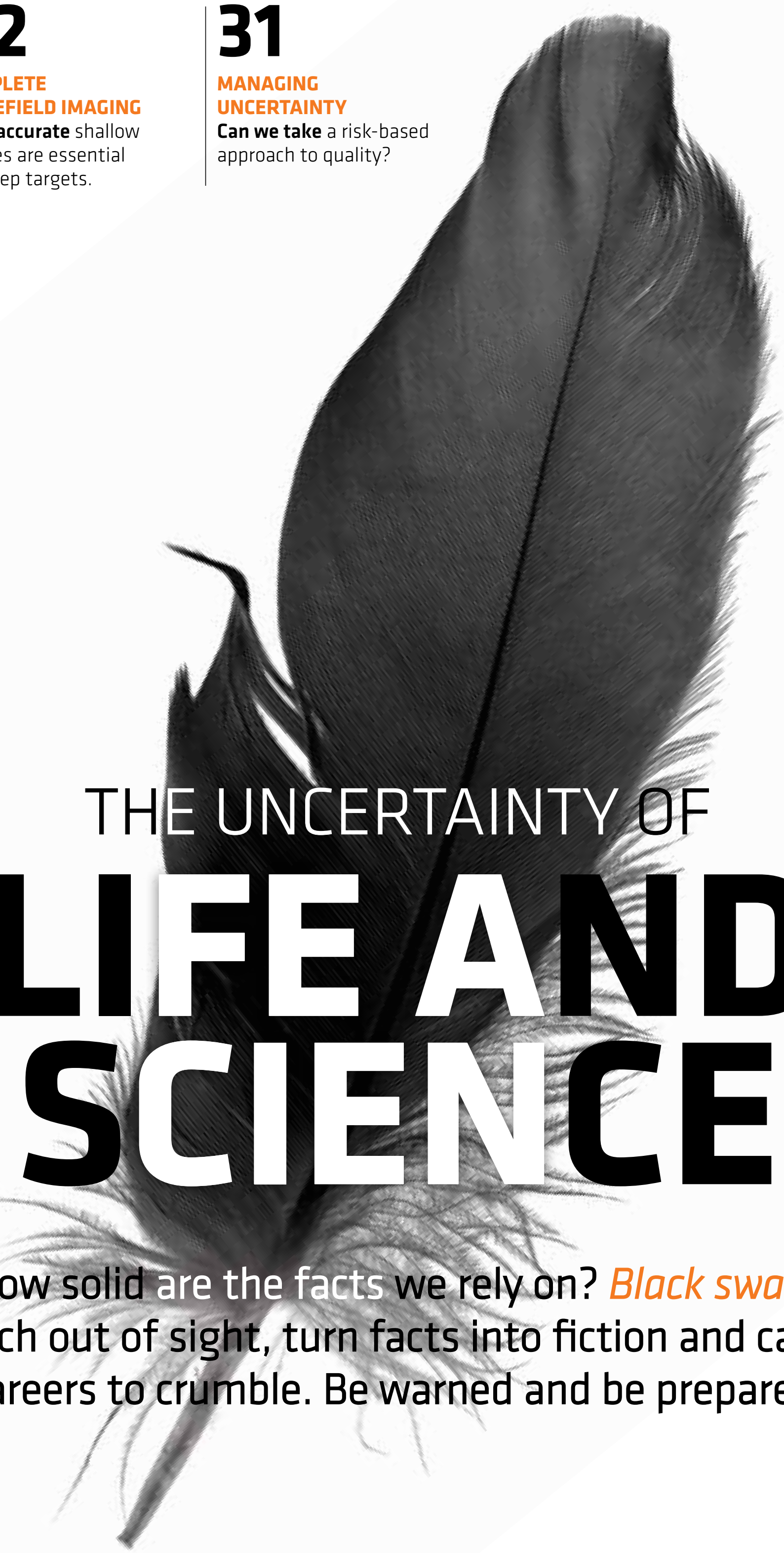

THE UNCERTAINTY OF

LIFE AND SCIENCE

How solid are the facts we rely on? *Black swans* hatch out of sight, turn facts into fiction and cause careers to crumble. Be warned and be prepared!

PGS

A Clearer Image | www.pgs.com

THE UNCERTAINTY OF

LIFE AND SCIENCE

In this issue Reflections looks into a field familiar to most exploration managers: managing uncertainty.

Nassim Taleb has made a fascinating study of the field, based on phenomena that appear without warning, turning facts into fiction, causing models to collapse and careers to crumble. He calls them Black Swans. How solid are the facts we rely on? According to Hans C. Rønnevik, Exploration Manager at Lundin, the problem is often not wrong answers but rather our failure to critically evaluate the questions. He threw away the accumulated knowledge and made the biggest find in the North Sea in a decade.

Seismic imaging can also suffer from false positives. It can be worth looking beyond the pretty pictures, to check the facts.

Two case studies look at how combining information from several wavefields can improve the reliability of our results, and the role of probabilistic workflows in reservoir characterization. We hope you enjoy the issue.

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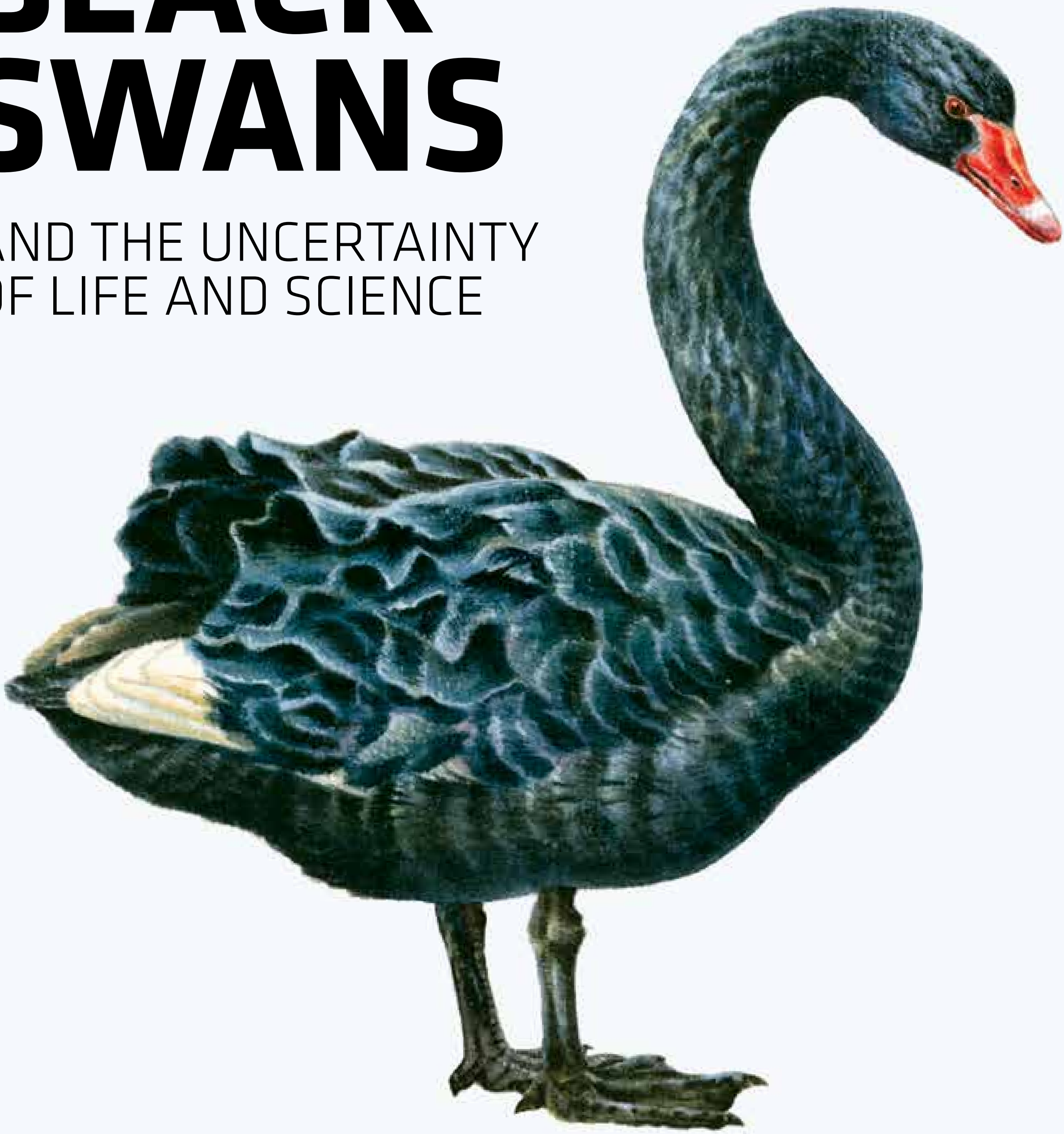
BLACK SWANS

AND THE UNCERTAINTY OF LIFE AND SCIENCE



Text Stein Arne Nistad **Photo** Dorling Kindersley (Getty Images)

What is truth? History and science are peppered by events that occurred like bolts from the blue and which suddenly and sometimes violently changed the course of knowledge. The mathematician and philosopher *Nassim Nicholas Taleb* calls them "Black Swans".

When these unexpected phenomena manifest themselves, with new perspectives and insight, established models, hypotheses and careers can crumble and fall like a house of cards, because they are based on incorrect assumptions. Changing truths can change life, science and the world as we know it.

Throughout time, experiences, theories and knowledge have been a prerequisite for development. They have also been a barrier to progress. As both experiences and hypotheses may be the consequences of wrong assumptions or interpretations, a perspective change may lead to fundamentally new conclusions. Some of the most famous examples of such changes are the publication of Copernicus' On the Revolutions of the Celestial Spheres in 1543, Einstein's theory of relativity, and the theory of quantum mechanics. These new approaches opened up a set of new paths of opportunity, changing science and our view of the universe. Great shifts in perspective have occurred from time to time throughout history.

The inverted pyramid syndrome

New scientific theories usually build on existing hypotheses. They add an extra layer. This means that new models and ideas are developed based on a set of unquestioned assumptions – which often are defined as facts or truths. It seems that our imagination is largely curtailed by our experience. It is almost like an inverted pyramid. Before Copernicus put the sun in the center of the universe, for example, scientists assumed that the stars revolved

THE **BLACK SWAN THEORY**

→ **The black swan theory or theory of black swan events is a metaphor that describes an event that comes as a surprise, has a major effect, and is often inappropriately rationalized with the benefit of hindsight. The theory was developed by Nassim Nicholas Taleb to explain:**

1. The disproportionate role of high-profile, hard-to-predict and rare events that are beyond the realm of normal expectations in history, science, finance and technology.

2. Why consequential rare events cannot be computed using scientific methods.

3. The psychological biases that make people individually and collectively blind to uncertainty and unaware of the significant role of the rare event in historical affairs.

Literature: The Black Swan – the impact of the highly improbable, by Nassim Nicholas Taleb

NASSIM NICHOLAS **TALEB**

- **Lebanese-American essayist, scholar and statistician, born 1960, whose work focuses on problems of randomness, probability and uncertainty.**
- **Taleb is a professor at several universities, and currently Distinguished Professor of Risk Engineering at New York University Polytechnic School of Engineering.**
- **His 2007 bestseller The Black Swan was described in a review by the Sunday Times as one of the twelve most influential books since World War II. In it Taleb criticizes risk management methods in the finance industry and warns about the inevitability of financial crises. He advocates what he calls a "black swan robust" society, meaning a society that can withstand difficult-to-predict events.** **Photo** GettyImages

around the Earth, and before that on the "incontrovertible truth" that the Earth was flat. In hindsight, it is easy to understand that these hypotheses led to many strange theories and models that were inconsistent with reality as we know it today.

Truth is a "relative" term

Sometimes even scientists mix up theory and truth. Newton, formulated in his time a body of physical laws voted so good, that many in the late nineteenth century defined them as the closest it was possible to come to a complete final model. There was no more to define or discover. Suddenly and from nowhere Einstein popped up, launching his theory of relativity. That theory turned everything upside down, as Einstein defined space, speed and time as relative terms. Einstein's theory brought us right into the nuclear age. Still it is important to remember that his and other scientific theories and models attempt to describe reality – they are not themselves reality.

Into the great wide open

Science continues to push new barriers in most areas and thereby faces new and amazing challenges. However, theory is not proof. So although everyone accepts the concept of gravity, there is still no proof of how it functions. Further, scientists still struggle to explain certain fundamental phenomena whose behavior is divergent to expectations. Problematic observations include pair-particles which interact instantaneously irrespective of the distance between them. This phenomenon challenges the idea that the speed of light is the absolute and maximum attainable speed in the universe. Quantum physics is concerned with phenomena that behave differently depending on the observer's intention. In other words, it seems that the observer's intention, or mental state, affects the result of the observation. This leads in turn to a scientific approach to a quite challenging question about consciousness: does matter create thought, or can thoughts create matter? This certainly adds new dimensions to the term uncertainty!

Does a deterministic world exist?

Humans like predictability and prefer to think that everything is deterministic. We consider the universe as a kind pool table, where it is possible to predict how the system will evolve after the first balls are set in motion. In practice it turns out that it is not that simple. Even relatively small dynamical systems may have complex behavior and so-called chaotic properties. This means that the system's complexity will evolve exponentially over time. The degree of chaos or unpredictability will increase to infinity over time. Consequences may be hard to describe and predict. That is why weather models tend to work fine for a week or so, and short-term weather predictions may be quite accurate. However, the complexity grows so fast that the computer power is not available to calculate longer time periods. Nassim Nicholas Taleb has developed a theory of how large dynamical systems develop. He sets out to explain why extreme and unthinkable events continue to occur in complex dynamic systems. Taleb considers both the systems' complexity and the tendency of the human mind to reduce complexity and risk by taking mental short cuts.

The black swan theory

Taleb's Black Swan theory is based on a simple metaphor. In short, most of us relate to the concept "swan" by only including white swans. This is simply because most of us have never seen swans of any other color, and hence we assume that all swans are white. We base all our thinking about swans on this hypothesis and so we create an inverted pyramid of ideas. The problem is that the initial hypothesis may be completely wrong, Taleb argues. Human beings tend to simplify their perspectives to exclude "unlikely" or extremely rare events: for example, what if there are black

IT IS NOT THE PREDICTABLE EVENTS THAT CHANGE THE WORLD

NASSIM TALEB

swans? Indeed, black swans do exist. In Australia, you can see flocks of black swans. This new fact raises another important question: do blue or yellow swans exist? Even after acknowledging that there are both white and black swans, most of us have trouble assuming that there may be swans in a splendid rainbow of different colors. We want the reassurance of what we know – namely the existence of only black and white swans. We base our worldview on it. This is what Taleb describes as the psychology that hinders us from taking into consideration the highly improbable.

Our world of statistics

Largely we make judgments based on common experiences, often in the form of data and models of our world. In many areas, we use statistical data to extrapolate reality. This applies in economics, weather, social sciences, technology and geophysics. In other words, most events we anticipate stem from statistical material, our experience and our interpretation of it. According to Taleb, it is not the predictable events that change the world, but the black swans. These events and phenomena are so improbable that they are hard to imagine and impossible to predict. Taleb claims that it is such unforeseen events that lead to the biggest changes in world history – simply because we are blind to their approach. They may be impossible to predict because the system that creates them, such as the world economy, is so large and complex that it appears to be "chaotic". Or it may be that they require new approaches, so fundamentally different from current practice that they are inherently unthinkable, such as Einstein's theory of relativity. In both cases, the events released are by nature unlikely to happen and therefore unthinkable. If major changes were possible to predict they would have been predicted and dealt with, concludes Taleb. It is the combination of low predictability and large impact that makes the Black Swan a fascinating puzzle.

Good and bad swans

There are in principle two types of Black Swans – good and bad. In general, the good ones have less impact. They evolve in our blind spot over time, opening new opportunities. One example might be discovering a new oil play, or a visual operating system that turns a phone into a personal stereo, a camera and a device for accessing the internet. New perspectives and scenarios may be driving forces for innovation, creativity and success. On the other hand, the bad Black Swans can seem to occur quickly and with devastating effect: like war, terrorist attacks and economic crises. On the latter phenomenon, Taleb states rather laconically, "The differences between a taxi driver and a financial analyst in economic crisis is the dress code and wages ... Beyond that they are both about as good at guessing."

So what is truth?

Some systems are so complex and dynamic that highly improbable phenomena and events occur from time to time. These catalysts for change may be understood and rationalized in hindsight, but cannot be predicted in advance. What we can do is look out for vulnerable systems. Bad Black Swans are going to occur whether we like it or not – and they are going to change the world. We simply have to deal with them. So let us end this story where it started. What is truth? In science and in life, very few things are certain and the truth is unlikely to be what we think it is. Only mathematicians deal in absolute proof. For the rest of us, hypotheses are built to be broken. What we think we know may not be the truth. And almost certainly the behavior of the dynamic systems around us will bring challenges, new perspectives and new understanding. In short, the future is most likely not what we expect it to be. ●

NEXT PAGE
FAMOUS **BLACK SWANS**

FAMOUS **BLACK SWANS**

"Black Swans" appear surprisingly often and in many different areas. They initiate dramatic changes and can change our "truths", way of life or our history. Still they are not always easy to spot, and we often don't fully understand what hit us when a new Black Swan is hatched ...

THE **LEHMAN BROTHERS BANKRUPTCY**

An ailing investment bank falls by more than 35 percent on the New York stock exchange, but a rally of energy stocks drags Wall Street up. The financial sector in the United States trembles and ponders whether Lehman Brothers can survive. Lehman stocks plunge 36.97 percent to $ 4.56 share. This was one of countless news stories on **September 11, 2008** describing a situation that led to one of the largest bankruptcies ever, USD 579 billion. The Lehman Brothers collapse marked the start of a global economic crisis that still reverberates.

In retrospect, the crisis is easy to understand. Debt-financed growth caused the relationship between investment and equity to decrease from 24:1 in 2003 to 31:1 in **2007**. In a growing market, the profit opportunities were huge, while the risk increased dramatically. Most of Lehman's investments were in the housing market, where a small decline (only 3.4%) eliminated all the equity in the bank. Few saw the crisis arising and understood the extent of it. Mathematician Nassim Nicholas Taleb argues that the global economy is so large and complex that it is by its nature chaotic, with a very high 'Black Swan' potential. In consequence, most banks and investment companies operate at much higher risk than they realize and understand. Hence, new economic crises with devastating effect will probably arise from time to time.

Photo GettyImages

THE **T FORD**

"I will build a motor car for the great multitude ... it will be so low in price that no man making a good salary will be unable to own one and enjoy with his family the blessing of hours of pleasure in God's great open spaces ... When I'm through, everybody will be able to afford one, and everyone will have one. The horse will have disappeared from our highways, the automobile will be taken for granted... and we will give a large number of men employment at good wages."

When Henry Ford introduced his Model T or **Tin Lizzie** October 1st **1908**, he revolutionized industrial production. Though Ford Motor Company was founded in 1903, people had been producing cars for decades. The Model T was the company's 19th prototype and production model. Ford made cars available for everybody, not only the rich. His production methods included moving assembly lines and completely standardized interchangeable parts. This reduced costs dramatically, leading not only to a remarkable increase of market share, but a totally new infrastructure of roads, gas stations, motels, and drive-by-restaurants to mention but a few. It also generated a ravenous thirst for hydrocarbons. From 1908 to 1927 Ford produced fifteen million Model Ts and became the true father of mass motoring.

Photo iStock

THE **FOSBURY FLOP**

The Olympic Games in Mexico **1968** was legendary for several reasons. It was the highest games ever (2,240m above sea level). It marked a milestone in America's civil rights movement – as the iconic photograph of two black American sprinters standing on the medal podium with heads bowed and fists raised represents. Bob Beamon's wonderful, fluke, long jump of 8.90 meters improved the world record by 55 cm, a record first beaten 23 years later.

However, the Black Swan of the Games was the high jumper **Dick Fosbury** who introduced a whole new approach to his sport. He ran in an arc towards the stand, rotating away from the bar as he leapt, in a breathtaking acrobatic exercise that employed a different set of dynamic forces than previous techniques. He won the gold medal, improved the world record and introduced the Fosbury Flop. This style is still predominant today and makes it possible to jump higher than ever.

Photo iStock

THE **BERLIN WALL**

The Berlin Wall produced two black swans. The first hatched on the night of **August 13, 1961** when the DDR sealed its borders with barbed wire and armed guards. Officially, the aim was to protect its citizens against fascism, while the underlying reason was to prevent them seeking freedom and higher wages in the West. It was a signal to the communist federations of Eastern Europe to toe the Soviet line. As the wall shot up the cold war got even colder. Around 1,300 children visiting East Berlin on the day the wall was sealed did not come home until three months later.

When the **Berlin Wall** fell in November 1989 it was equally shocking. Perestroika and pressure from the East German population to remove travel restrictions were the drivers, but the wall fell almost by mistake. During a live broadcast of a press conference, DDR leader Schabowski read out a council decision on proposed new travel rules, although the decision was not yet formalized. Thousands of DDR citizens flocked to the wall. Under pressure from the masses, the guards at Bornholmer Straße opened the crossing. Soon other crossings followed suit. This led within a year to a reunification of Germany – which no-one had envisioned or dared to predict before the wall came down.

Photo iStock

THE **TESLA MODEL S**

Is Tesla the new T-Ford? Some people claim that Tesla entrepreneur Elon Musk has not only revolutionized the electric car but is also revolutionizing the automotive industry. In June **2013** Tesla's sleek electric sedan outsold Porsche, Fiat, Buick, Jaguar, Land Rover and five other companies in California.

The vehicle came top in tests conducted by Consumer Reports. The US National Highway Safety Traffic Administration gave it its highest safety rating. The **Tesla** outperforms most gas driven cars, and appeals to people that would otherwise never consider buying an electric car. Customers claim that the "green" profile is just an extra benefit and the Tesla Model S is simply a very attractive luxury sedan compared to every standard.

Critics meanwhile claim that Tesla is a company built on loan guarantees, sustained on subsidies and profitable only through a system of credits designed to benefit electric car manufacturers at the expense of their competitors. Supporters counter that Tesla's success is primarily due to Elon Musk's marketing genius. His tactical use of social media means a tiny car company has the best-known financing program in North America. A new Tesla SUV and a cheaper mass-market sedan are on their way. It is still to be determined if Tesla truly harbors a Black Swan under the hood that could revamp the automotive industry and challenge petroleum as the main fuel. Hype or revolution: time will tell! **Photo** Tesla Motors

THE **SHALE OIL REVOLUTION**

This benign Black Swan has turned around the fortunes of the US exploration business, averted the peak oil scenario, and altered the geo-political significance of the Middle East.

According to the latest BP annual statistical review of world energy, the biggest production increases in the world occurred in the USA, which enjoyed the largest gain in oil production in its history. The US Department of Energy **July 2014** drilling productivity report noted that three regions, Bakken in North Dakota, Eagle Ford Shale and Permian in Texas have passed the magical production milestone of 1 million barrels of oil per day. There have only been ten oil fields in the world that have ever achieved this. The significance of these new plays to US oil output is enormous and production is still rising.

The shale story was born as a result of new drilling techniques (fracking and horizontal drilling). The breakthrough was combining the two, around 2008. The result has radically altered the dependence of the world's largest oil consumer on imports from other countries. The USA may be oil self-sufficient within a decade.

Without shale oil and gas, rising fuel prices could have had a devastating effect on the global economy. **Photo** Shutterstock

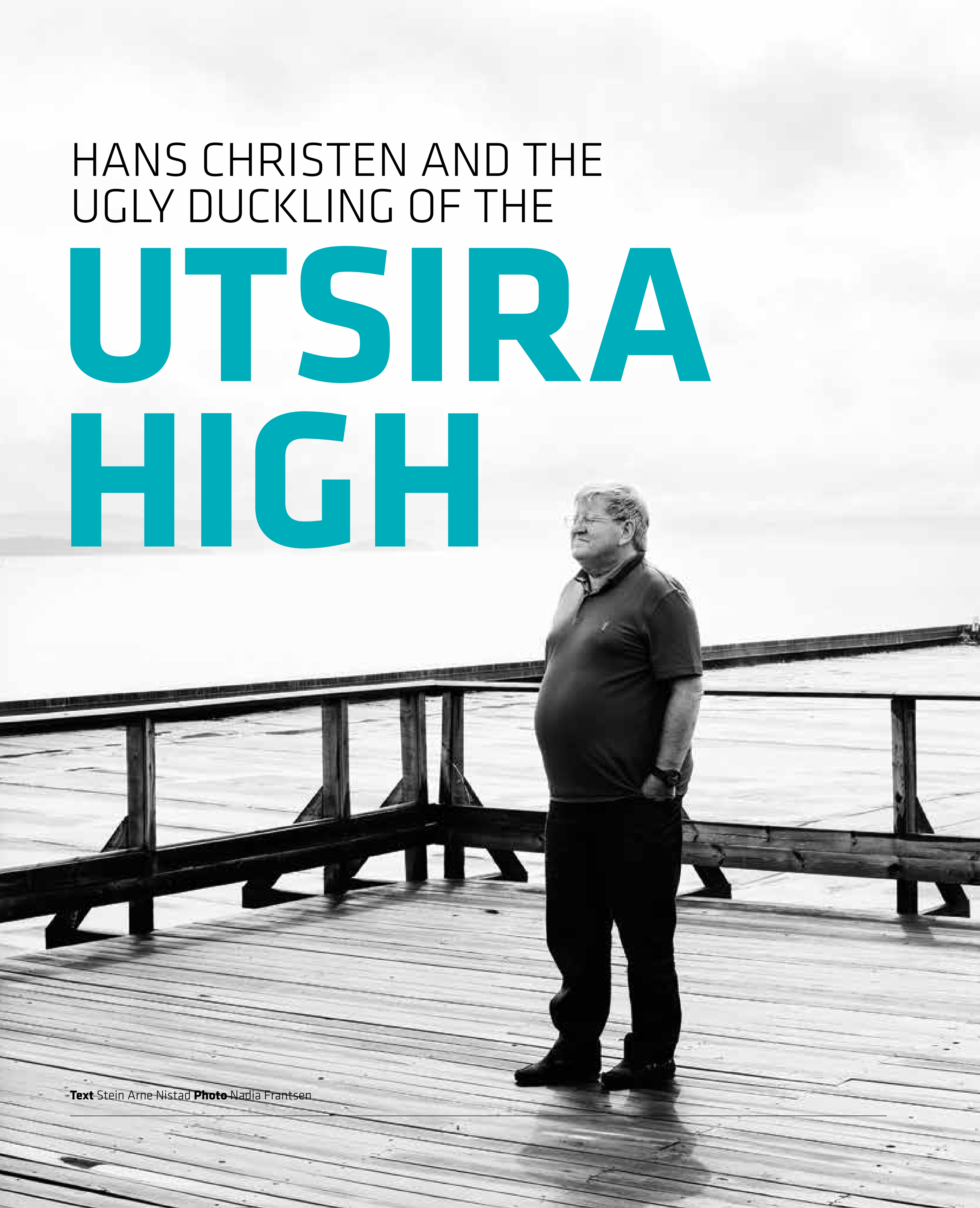
GEOSTREAMER

The launch of GeoStreamer in 2007 cracked a problem that had defeated the seismic industry's best brains and deepest pockets for decades: the ghosting connected with towed seismic.

Inventor Rune Tengham considers true innovation to be a fundamentally random process. Inspired by an underwater defense technology event, he was aided by a great development team, the right company contacts to jump-start the project, and abetted by a new corporate direction focused on technology. Seven years on we are still exploring the repercussions of the new wave that GeoStreamer launched: broadband has radically changed the industry's expectation of signal penetration, data resolution and interpretability. New opportunities continue to appear beyond mere bandwidth and aside from pure imaging.

Using the GeoStreamer separated wavefield we can now extract new intelligence from the Earth, enabling us to delineate prospects, and describe the structure and key properties of reservoirs even in frontier areas without access to well data. We are learning to harness our old enemy the multiple to improve sub-surface illumination and use each wavefield component separately, to cross check the others and enhance the total result. What's next? **Photo** PGS

HANS CHRISTEN AND THE UGLY DUCKLING OF THE UTSIRA HIGH



Text Stein Arne Nistad **Photo** Nadia Frantsen

Lundin Petroleum made its entry into exploration and production on the Norwegian shelf in 2003 and within five years had succeeded beyond all expectations. Within a decade they had identified one of the largest oil fields in the North Sea, on the Utsira High. An unlikely duck became a huge black swan. How did *Hans Christen Rønnevik* manage to find new opportunities in an area where others had explored for nearly forty years?

We meet Hans C. Rønnevik outside Lundin's headquarters in Oslo. He's just back from vacation in Spain and according to the lady at the front desk he really deserved his holiday. Rønnevik works day and night. Today he arrived later than usual, a little before six in the morning. Do you get tired of working so much? "No, you don't get tired of positive stress." He reveals a deep rooted fascination and knowledge about oil exploration in the North Sea.

Old school pioneer

Rønnevik is one of the pioneers of Norwegian oil exploration. In 1972 he left the University of Bergen with a degree in geology and crossed the road to what would become the national petroleum agency. It was this institution that built the structure for the oil industry in Norway, and the foundation of the country's future economic wealth. His 45-year career also included time with Saga Petroleum and a number of other oil companies before joining Lundin. In short, there are not many people who know more about the oil fields and geology of the North Sea. Under his management, the exploration team at Lundin has provided some of the most surprising and the largest discoveries in the North Sea in recent years. They have found oil in places that the rest of the industry had almost given up on after nearly forty years of exploration. How is that possible? Is there a simple explanation?

Exploration is continuous unfolding of reality

Rønnevik takes an unexpected angle to the question. He suggests that perhaps it is his approach to life and organizational philosophy that makes the difference. What affects an organization's ability to realize ideas? According to Rønnevik, great ideas are of no use if the organization lacks the culture and courage to test and implement them. Taking risks is a fundamental precondition. Moreover, he says, many fall repeatedly into the trap of confusing direct and indirect data.

"We can have all sorts of nice models and tons of seismic data to substantiate the geology – and create opportunities to discover oil. But they are still only models of reality – it is not reality. It is only once we have evidence about the real geology and compare that with the models, that we can begin to draw correct conclusions. Therefore, we base all our exploration on the experiences found in the form of seismic data and, equally important, the core samples or other information available from the area. If they do not exist, then we need to drill to confirm our hypothesis. In short, it's about the will and skill to adapt to reality!"

Perspectives

Rønnevik argues that it is also about seeing things in a new light and explains, "When we start to look at a field, especially in an area where we believe there may be hydrocarbons, and where other companies have concluded that it is unlikely, we are extremely careful to clean up the existing hypotheses. Often it turns out that the hypothesis was formed before the data was collected, the seismic was acquired and the exploration well was drilled. This means that the entire analysis and approach were biased by the initial hypothesis and hence the conclusion might be wrong. What we attempt to do at Lundin is to free ourselves from the existing hypothesis and rather try to reveal what the data in front of us actually tells us about reality. How does it help us to see where we need to know more, and what kind of information do we need to reveal that reality? On Utsira the general hypothesis was that there might be a gas reservoir. This affected all subsequent analyzes and conclusions. In most cases, you find what you are looking for. If you are are looking for gas you may find gas, but

THE JOHAN **SVERDRUP FIELD**

- **Johan Sverdrup is an oil field in the North Sea, about 140 kilometers west of Stavanger, Norway. The field lies in two different production licenses and consists of two different discoveries: Avaldsnes (operated by Lundin Petroleum) and Aldous Major South (operated by Statoil). When it was revealed that these discoveries constituted one single field, it was renamed Johan Sverdrup.**

- **Production startup is expected in 2019. Peak production is estimated to be over 500 000 barrels per day, which will make it by far the largest producing oil field in the North Sea by the time it reaches its peak.** **Illustration** Statoil

you most certainty are not going to discover oil. When we dropped that hypothesis and started analyzing the data and core samples from the perspective that there might be oil deposits at Utsira, the picture changed completely and the conclusions accordingly."

Avoid conjecture

Rønnevik argues, moreover, that from an exploration perspective it is far more important to uncover what has happened, than understand why it happened. Those theories will at best explain the background to the model. They may be completely wrong and lead to the wrong conclusions. To understand what has happened, in terms of what the geology actually looks like and how the layers are built up, and to understand what that reality means, is far more important. When it comes to Utsira, we focused on finding new approaches and that led to a breakthrough. In Norway we have something called Petrobank, where all oil companies are required to publish the results of their search for oil. After ten years, anyone can access the information. In Petrobank we found data from the 1990s, and we processed them using new methods. Then we used PGS GeoStreamer to get new and far more detailed 3D seismic. It was crucial for understanding the field.

Reality beats fiction

The conditions at Utsira are highly unusual. The field is raised up and flat on top, squeezing the geology into much thinner layers than usual. In practice, this meant that the most interesting part of the geology was compressed beyond seismic resolution. We are talking about squeezing 50 million years of geology into just 22 meters. We needed to get to the core samples to be able to unlock the truth about the geology of these layers. These provided a new insight and led to the discovery of oil. The very first well we drilled on the Utsira High in 2007 resulted in the Edvard Grieg discovery and importantly it was this discovery that provided the key to unlock the puzzle of the geological setting in this area. Since Edvard Grieg, Lundin Norway has made five additional discoveries on the Utsira High with Apollo, Tellus, Luno South, Luno

HOW TO BUILD A **PURPOSE-ORIENTED CULTURE**

1. **Find a unique purpose**
2. **Create culture of honesty: walk the talk**
3. **You need vision and knowledge to withstand a rainy day**
4. **Creative learning is both a team and individual process, dependent on maximum diversity and freedom to think and challenge**
5. **Appreciate the learners**

YOU FIND WHAT YOU ARE LOOKING FOR

HANS CHRISTEN RØNNEVIK

II and finally the giant. Johan Sverdrup is one of the largest fields in North Sea. It was discovered in 2010 and production is planned to start 2019.

Who needs to join in?

According to Rønnevik, Lundin's success is partly down to organizational strategy. They consciously set up a small, efficient, organization yet with sufficient authority and diversity: competence, attitudes and personal characteristics. Authority is a key word. It was during a potentially disastrous underground blowout in a North Sea well, that Rønnevik learnt that crises require a very different type of leader than the conventional "theoretical" manager. Models and organizational hierarchy are fine for traditional operation. In a storm and surrounded by uncertainty it becomes clear who is ready and capable of taking command. Crises reveal who has the strength to step forward, the ability to handle the pressure and the knowledge and courage to think and test "out of the box" solutions.

– There is a big difference between a production organization and an organization built for exploration, innovation and problem solving. In Lundin Exploration, we need people who are able to stand on deck in a storm. And we try to eliminate the "self-referring" syndrome. In too many organizations established truths remain established truths. Accepted facts are rarely challenged or tested. The Lundin team is a varied group both in terms of education and experience, and also personal characteristics. We try to maintain a challenging and competent environment, with people who are able to see the same problem from very different perspectives – and who can tolerate and thrive on stormy debate to test out their new ideas.

Scaling new heights

Throughout the interview Rønnevik reveals various sources of inspiration both philosophical and commercial.

– Stability is based on conceptual changes, he says. Many companies base their future on what works today. The problem with that is that the world evolves. Look at Nokia and Ericsson. They were swept away because they were not sufficiently focused and devoted to explore new opportunities while they harvested. At Lundin, we focus on developing new approaches and exploration methods, and trying out new technologies. We need to be able to harvest, explore and develop simultaneously. To survive in the future we need to be a part of the conceptual change.

A low hit rate is good

Suddenly Rønnevik presents an unusual perspective. "For a while I worked in a company where we had a 70% hit rate on new oil discoveries. That may sound good but it is really an enormous problem. What it shows is that the organization only explored certain winners – they avoided anything that was more uncertain. In other words, the exploration team worked almost like a production unit. I believe that around 50% is much healthier, because then we innovate too. Facts are experience – part of the truth but not the whole story. The truth should contain but not be constrained by the facts, says Rønnevik and ends the interview with a quote related to the limitation of truths and facts, "To know what thou knowest not is in essence omniscience," (Piet Hein). ●

6

Best practice may be a trap: develop continuously better practice by applying developing tools

7

Don't get caught up in the words of your own propaganda

8

Be focused and defocused simultaneously

9

Prioritize facts and not fiction

10

Avoid the empty raincoat syndrome (form without content)

CHAOS VS DISORDER

Yakov G. Sinai claims that he was neither specially gifted nor interested in mathematics when he grew up. Despite that, this year's Abel Prize Laureate has penned a prolific body of groundbreaking work related to dynamical systems and chaos, giving names to everlasting mathematical terms like "Sinai's random walk" and "Sinai's billiards".

Text Stein Arne Nistad **Photo** Linda Cartridge **Illustration** Jon Arne Berg / By Hands

When Yakov Sinai entered the University Aula in Oslo to receive this year's Abel Prize, an award as rare and prestigious as a Nobel Prize in physics or medicine, the gathering of dignitaries and great minds was one of the smartest likely to attend an event in the Norwegian capital this year. On the walls, eleven monumental murals by Norwegian artist Edvard Munch illuminated the vast hall with images of northern light and the ages of man. The audience included academics from home and abroad, national and international press, and a broad selection of people all with an above-average interest in the field of mathematics. The musicians entered the scene and the youthful Crown Prince Haakon, representing his father, handed over the beautiful and weighty Abel prize almost deferentially to the slightly stooped, academic giant.

A long and winding road

Sinai, now almost eighty, has been a prolific thinker almost all his life. In the course of his career he has published over 250 scientific articles, and his contribution to the field of mathematics and physics has been significant. He has created concepts and scientific terms that will forever bear his name, such as the Kolmogorov-Sinai entropy, Sinai's billiards, Sinai's random walk, Sinai-Ruelle-Bowen Measures, and Pirogov-Sinai theory. For most of us those concepts are as incomprehensible as they are profound for the initiated. Mathematics at this level is not for wimps.

Sinai was ten when the Second World War drew to an end and the iron curtain was thrown over Europe, separating East from West. As an academic with his head full of the theoretical consequences of playing billiards in space, Sinai avoided much of that political and cultural evolution. For most of his career it focused him on the academic community in the USSR. Nowadays he is free to live and work in both Moscow and Princeton. Sinai remains an active part of the scientific team at The Landau School outside Moscow.

What to do?

It was never a given, explains Sinai, that his career should be in mathematics. As a child, he was not bothered with the subject, and he claims that he was not gifted nor had a special mathematical talent. Though he was good at chess and other logic games, he much preferred football. However, it was no surprise that young Yakov should become an academic, following both parents and his grandfather. When he finished high school his parents, who were microbiologists, pressed him to pick his path. Sinai's grandfather and half-brother lobbied hard for him to choose mathematics. Sinai claims he was too weak to resist the pressure, and so more

OFTEN WE CONFUSE CHAOS WITH DISORDER

YAKOV SINAI

or less by chance he ended up a mathematician. It became his life, night and day. He is married to Elena B. Vul who is both a mathematician and a physicist, and they have published several joint scientific papers.

It's all in the mind

It takes time to deal with mathematical problems. Yet Sinai has been extremely productive launching over fifteen different mathematical theories over almost 60 years. It typically takes him several years to solve a complex mathematical problem, with 24/7 attention, he explains. In the most intensive period there is no room to think about anything else, because solving a mathematical problem requires full concentration. At this stage he writes almost nothing down. It is all in his head.

But what about documentation? Sinai responds with a sly twinkle in his eye. Writing the scientific paper is the least interesting part, he claims. It's boring because the problem no longer exists, it's just a record of the solution. Although he may not relish writing, Sinai is reputed to be a great teacher and he has overseen more than 50 PhD candidates. He claims that the happiest professional moments are when he gives the first lecture to present a new theory, because it is both exciting and also provides new insights for himself.

So what is required to become a good mathematician? Sinai thinks about it for a while before he responds. “First intuition,” he says. “Then mathematical techniques and it is also wise to have some mathematical knowledge. However, the most important thing is that you enjoy what you are doing.”

Chaos is not disorder

“Often we confuse chaos with disorder,” says Sinai. “When my wife complains that my office is a mess – she might describe the piles of books, papers and cups as chaotic. This is not chaos. It is disorder. Chaos is a term that indicates a form of complexity. We could for example never have a university faculty of disorder, but we can study chaos. The interesting thing is that I worked with chaos theory long before the term existed. I was studying the relationship between order and chaos when I was developing the use of probability theory and measure theory in the study of dynamical systems. If for example, we examine a system that on the surface seems orderly, we often find that as we study it deeper, the degree of chaos increases, while the opposite is rarely the case. Chaos theory is really a term we mathematicians have borrowed fairly recently from physics. When the physicists introduced the term “chaos theory”, we had no choice and had to use the same term – even if the content in itself is a little different.”

What is chaos?

So what is Sinai's work about? In simple terms, he looks at the question of how and why random behaviors can occur in purely deterministic systems. Chaotic phenomena are highly sensitive to initial conditions. In the physical world, we are surrounded by such complex systems. The most obvious example is the atmosphere, where temperature, humidity and pressure create weather systems around the globe. Popular science has dubbed this the 'butterfly effect'. In the 1960s, Sinai developed a method to define the extent to which such systems are chaotic or deterministic. He has revealed that it is mathematically possible to prove the degree of complexity of a dynamical system. The core of whether a system is deterministic, or whether it has chaotic characteristics, is revealed by how the system evolves over time. In a chaotic system, the number of possible states of a set of input conditions develops exponentially over time, while a deterministic system will evolve linearly over time.

Sinai's billiards

One of his best-known theories is called "Sinai billiards", a mathematical model of chaotic motion involving scattering billiards with convex obstacles. The model is based on a billiard ball set loose on a billiards table with an object lying in the center, such as a circle. He imagines a theoretical billiard ball that does not lose speed, reflected infinitely on the table. If the ball is set in motion on the table within a spread of an angle, will its trajectory evolve linearly or chaotically? Sinai proved that on a traditional, rectangular, table the motion of the ball will be linear and ergodic. With a concave boundary in the middle of the table, the system that evolves will be chaotic. This means therefore that the number of possible positions and trajectories on the pool table will develop exponentially over time. Sinai billiards has been used to model and verify the laws of statistical physics, including Einstein's 1905 diffusion equation.

The Kolmogorov – Sinai entropy

In collaboration with his teacher Kolmogorov, Sinai helped define an invariant known as the Kolmogorov-Sinai entropy. This invariant defines the complexities of a system, meaning that a given system would never exceed its highest fixed complexity. This is used to classify and model dynamical systems. A number of Sinai's theories are also extremely useful for physicists and included in the toolbox of mathematical physics.

Physics vs mathematics

Sinai explores the boundary between physics and mathematics. Physicists he explains often base their work on hypotheses, while mathematicians have to prove that things are true – always and forever. Put simply, a physics thesis is considered scientifically robust as long as it does not conflict with other hypotheses or experience. The mathematician must propose a thesis that will never conflict with mathematical theories or itself. A mathematical proof holds forever. Thus, mathematics is the only exact science, though it advances very slowly. Mathematical proofs are truths. He pokes a little fun at the fundamental dichotomy between these two approaches in an article entitled "Mathematicians and Physicists = Cats and Dogs?"

"So a physicist may perceive my mathematical proof as trivial. Of course, they say, we already knew that!" In physics they consider theories as facts. Sinai is highly respected in both the physics and mathematics communities as the major architect of the most bridges connecting the world of deterministic (dynamical) systems with the world of probabilistic (stochastic) systems.

Models and reality

We are keen to hear if Sinai has any thoughts on the field of seismic exploration. Sinai draws a clear distinction between theory and reality. "My work is to create a mathematical understanding, theory and a toolbox that can be used to develop models of dynamical physical systems."

"For example, at the moment we are studying the dynamics of tornadoes. They represent a complex chaotic dynamical system, but which is so limited that it may be possible to create usable mathematical models."

He is unfamiliar with the challenges of illuminating the subsurface using reflected sound waves but considers that these systems too may have interesting chaotic characteristics. The problems and complexities of measuring wavefields and analyzing their reflections within and beneath layers of salt seem to interest the great mathematician. Perhaps the complexities of the subsurface can inspire a new dimension to this illustrious career? ●

YAKOV G. **SINAI**

- **Born 21 September 1935 in Moscow. BSc (1957), Ph.D. (1960), and doctorate (1963) from Moscow State University. His advisor was the prominent Andrey Kolmogorov.**
- **From 1960: Scientific Researcher at the Laboratory of Probabilistic and Statistical Methods at Moscow State University.**
- **1971: Professor at Moscow State University and Senior Researcher at the Landau Institute of Theoretical Physics, Russian Academy of Sciences. Since 1993 Sinai has also been a Professor of Mathematics at Princeton University, USA.**
- **1997-1998: Thomas Jones Professor at Princeton University.**
- **2005: Moore Distinguished Scholar at the California Institute of Technology in Pasadena.**
- **Yakov Sinai has written more than 250 research papers and a number of books. He has achieved numerous groundbreaking results in the theory of dynamical systems, in mathematical physics and in probability theory. Many mathematical results are named after him, including Kolmogorov-Sinai entropy, Sinai's billiards, Sinai's random walk, Sinai-Ruelle-Bowen measures, and Pirogov-Sinai theory.**

THE **ABEL PRIZE**

ABEL
PRISEN

- **This has often been described as the mathematician's Nobel Prize and is an international accolade presented annually by the King of Norway to one or more outstanding mathematicians. Named after Niels Henrik Abel (1802–1829), the prize was established in 2001 by the Government of Norway. It comes with a monetary award of 6 million Norwegian kroner (approximately USD 1 million).**

- **PGS supports the work of the Abel Committee through its sponsorship of the Norwegian Academy of Science and Letters.**

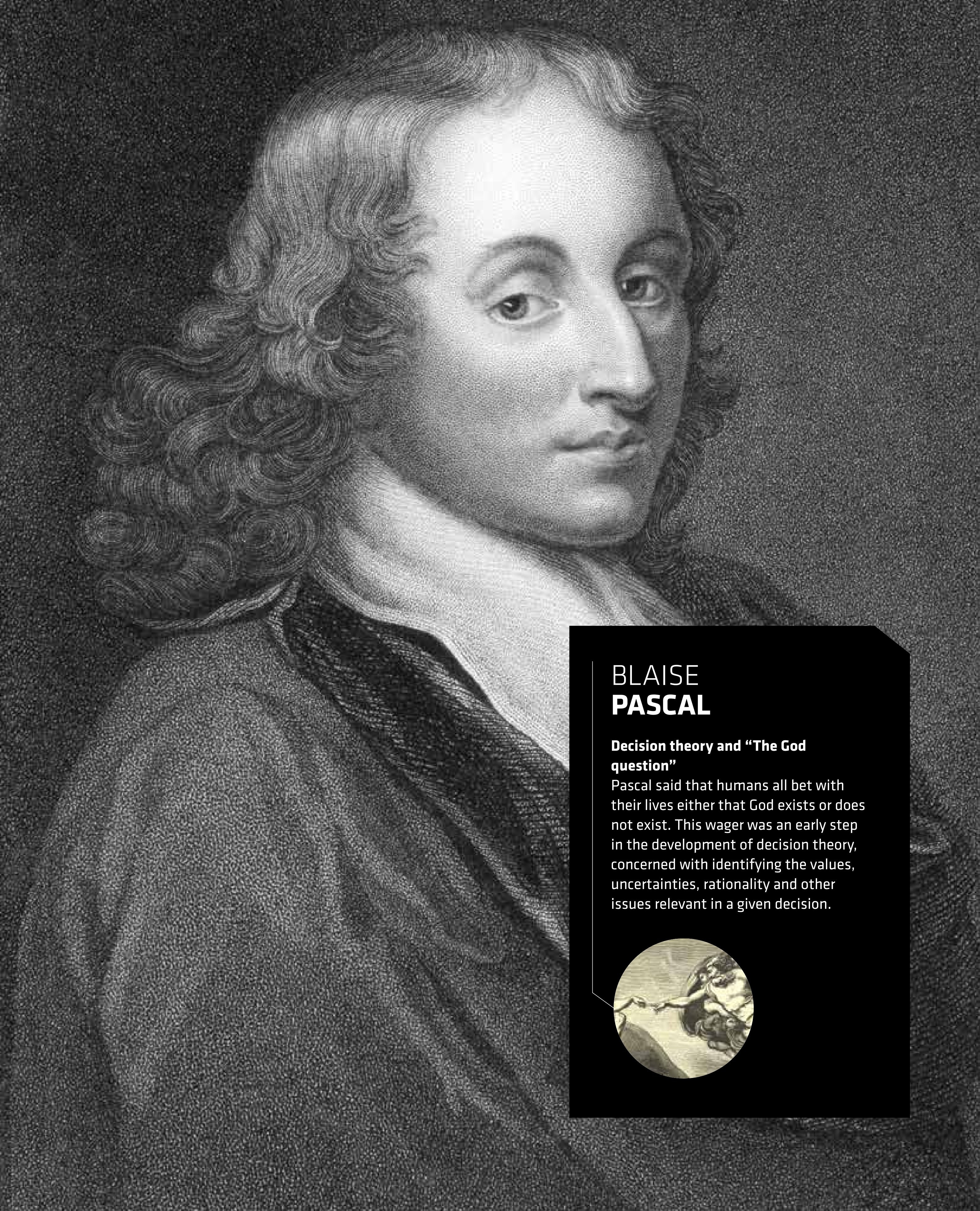
PROBABILITY:
CHANCE OR SCIENCE?

"God does not play dice with the universe," Einstein famously declared. However, probability theory arose from a game of dice.

Text Andrew Long **Photos** iStock / GettyImages / Shutterstock

CHEVALIER **DE MÉRÉ**

In 1654, **Chevalier de Méré,** a French gambler, instigated a correspondence between the mathematicians Blaise Pascal and Pierre de Fermat. The outcome was the first fundamental principles of probability theory. In the 1800s, Pierre de Laplace was the first to assign probabilities to hypotheses and applied this to many scientific and practical problems, a pursuit that continues to this day.



BLAISE **PASCAL**

Decision theory and "The God question"

Pascal said that humans all bet with their lives either that God exists or does not exist. This wager was an early step in the development of decision theory, concerned with identifying the values, uncertainties, rationality and other issues relevant in a given decision.

LIFE, DEATH **AND TAXES**

In the 17th century probability theory and the concept of expectation solved the estimation of the fair price for an annuity, a problem that had flummoxed even the great Isaac Newton. Hence, the emergence of probability theory had applications to events in life, events after death, and matters of taxes!

Making better predictions
The posthumous publications of eighteenth century reverend Thomas Bayes led to Bayes' theorem. This is in many ways to probability what Pythagoras' theorem is to geometry, and expresses how a subjective degree of belief should rationally change to account for evidence.

THE GAME **OF LIFE**

A general criticism of decision theory is that it considers the "known unknowns", not the "unknown unknowns". The "butterfly effect" describes how tiny events can influence vast systems. Significant events may be outside the model, as in black swan theory. Still we are fascinated by efforts to describe economics, physics, and social behavior in probabilistic terms. Although we may not be able to understand the details, we are all gamblers in "the game of life".

COMPLETE WAVEFIELD IMAGING

Seismic images need to provide accurate information throughout the entire subsurface strata: from the seabed down to the reservoir. For without solid knowledge of the shallow geological environment there can be no certainty that our calculations regarding the deeper reservoir layers are correct.

Text Volker Dirks **Data** Johan Sverdrup **Images** PGS / Lundin

CWI

- Complete Wavefield Imaging (CWI) is a data imaging workflow developed using the various wavefield outputs from GeoStreamer.
- The application of CWI on the Johan Sverdrup field in the North Sea led to a step change in the accuracy and detail of the computed near-surface velocities. As a result, channel structures were imaged with striking clarity revealing new details about the internal channel geometries and sediment fills.
- A detailed and precise near-surface model has improved the image of the reservoir section measurably, with an overall improvement in the match between seismic and well information. This in turn has increased the asset team's overall confidence in the structure and position of the reservoir rocks, reducing uncertainties surrounding the estimates of total hydrocarbons reserves in place.

Producing a detailed and accurate image of the reservoir rock and the geological structures that contain hydrocarbons deep inside the subsurface is crucial for E&P companies, as it allows them to draw up detailed plans for placing wells so that oil and gas can be recovered most effectively. For decades 3D seismic has been the method of choice for creating such an image of the subsurface.

Unlike taking a picture with a camera which uses light waves to image an object directly in front of the lens, seismic technology is more similar to ultrasound, used to image the unborn fetus by seeing through the mother's body to focus on the child in her womb. Imaging a hydrocarbon reservoir with seismic waves is complicated, as many kilometers of rocks and sediment between the Earth's surface and the target, 'obscure' the view. Both the speed with which a seismic signal travels through these various rocks as well as the amplitudes of the sound waves that are reflected back to the surface need to be calculated very precisely to produce an accurate subsurface image. It is incidentally the rock formations in the very shallow layers nearest to the ocean floor which can prove challenging. However, it is precisely those very near surface layers that oil companies are increasingly concerned about, since they need to know if these pose any hazards for drilling equipment and other production infrastructure and also need to ensure that no oil or other production-related contamination occurs through existing or newly created fractures and pathways.

Local gas accumulations or paleochannels filled with soft and unconsolidated sediments can also have a serious effect on the propagation of seismic waves and our ability to create a reliable reservoir image.

More than the sum of its parts

So, how can we address the challenge of computing accurate velocity information in areas of complex shallow overburden geology? The answer may lie in a new processing workflow that makes use of various wavefield recordings in the GeoStreamer® deghosting procedure. GeoStreamer was developed to overcome the frequency range limitations of conventional towed-streamer acquisition systems. Traditionally, it was necessary to tow the recording equipment relatively shallow, at around 10m water depth, to avoid attenuation of high frequency content by the so called ghost notch effect. This phenomenon occurs at both the source and the receiver side and is inherent to all towed-streamer acquisition techniques. The ghost effect describes the gradual loss of signal of a range of frequencies through destructive interference of directly reflected seismic energy from the subsurface with ghost reflections of the same energy at the sea surface directly above the source or receiver

3 SEPARATE WAVEFIELDS

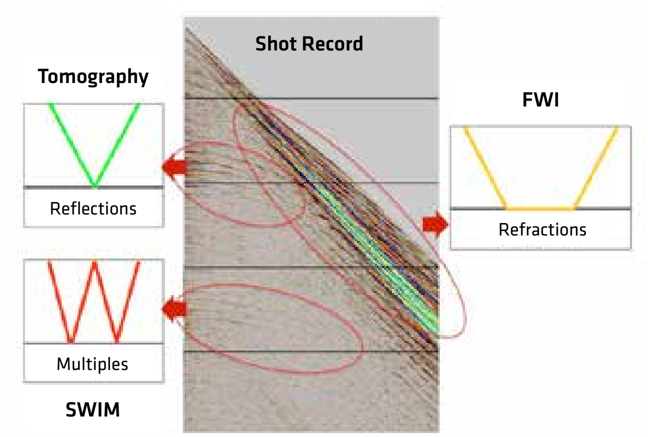


FIGURE 1: CWI is made possible by the separated wavefields available with GeoStreamer: FWI uses refractions, SWIM adds multiple illuminations and Reflection Tomography includes the primaries.

SINGLE SHOT PROFILES

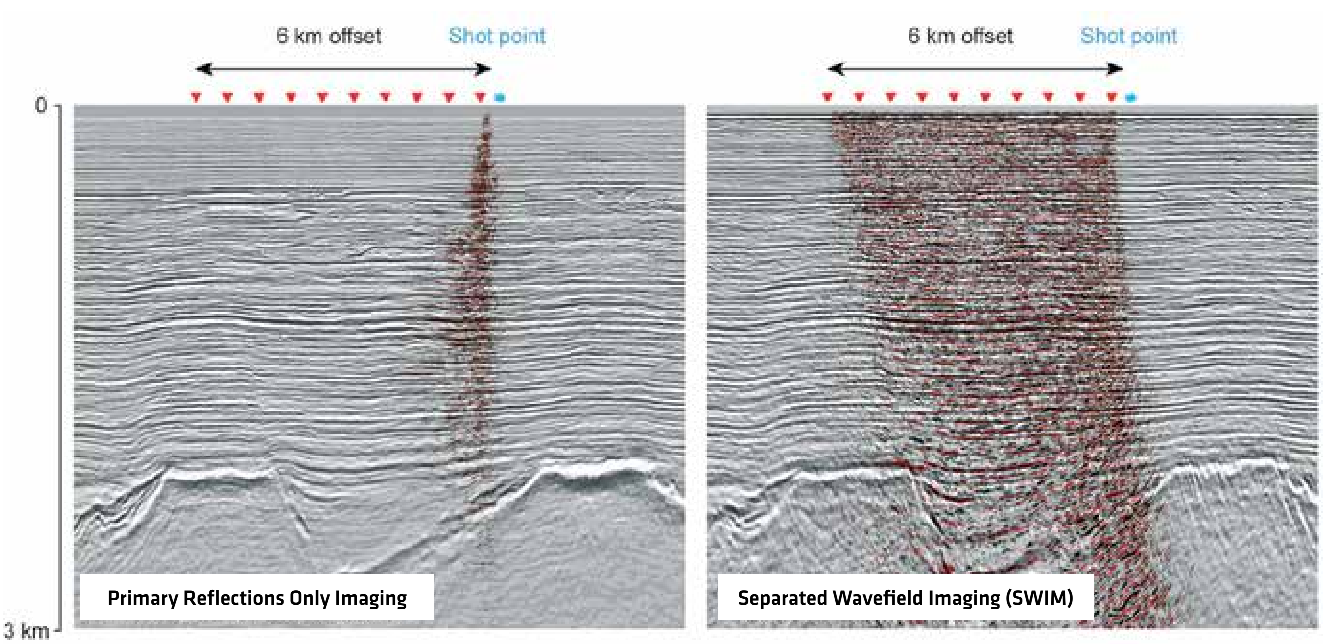


FIGURE 2: Note the greater spatial illumination provided by subsurface multiples in comparison to primary reflections. The lateral extent is limited only by the areal distribution of streamers. The image above was modeled for a 6km streamer.

UTSIRA HIGH

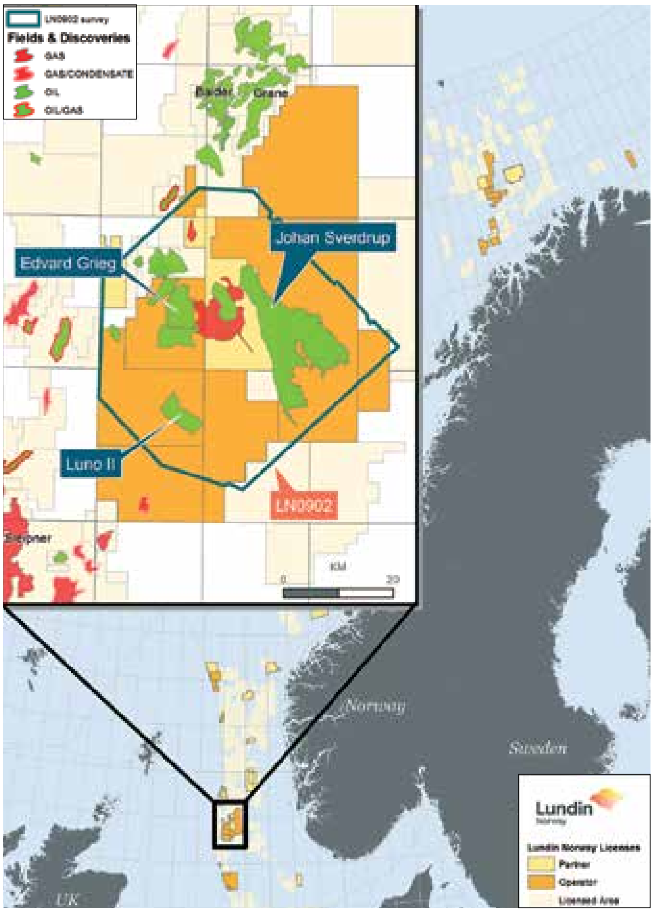


FIGURE 3: The fields in the southern part of the Utsira High in the Norwegian sector of the North Sea. The extent of the 2009 LN0902 3D GeoStreamer survey used for this PSDM study is indicated by the blue polygon. **Map:** Lundin

equipment. These interferences lead to a total cancelation of certain frequencies, whose ranges depend directly on the tow depth of both the seismic sources and the streamer recording system. The deeper the streamers are towed to improve the low-frequency content the more high-frequency content is attenuated by the ghost effect. GeoStreamer's co-located hydrophone and vertical velocity sensors record different properties of the same seismic wave. The ghost effect is removed from the data in a very robust and precise manner by simply combining the complementary recordings of these two sensors in a process which involves the calculation of local wavefield components.

It is those wavefield components, in addition to the original hydrophone and velocity sensor recordings, that are utilized in the new velocity model building and imaging workflow christened Complete Wavefield Imaging (CWI).

The CWI workflow is comprised of three main elements **(Figure 1)**: Reflection Tomography, Full Waveform Inversion (FWI) and Separated Wavefield Imaging (SWIM). The initial step – reflection tomography – ensures a globally consistent initial velocity model as a starting point for full waveform inversion, improving its stability. Dual-sensor streamer data that is very rich in low frequency amplitudes has been shown to further improve the resolution and accuracy of the shallow velocity model derived from FWI, resulting in an overall more accurate model for imaging. The final step of the CWI workflow consists of computing SWIM gathers. This breakthrough technology allows us to image the Earth with a much more extensive subsurface illumination, by including free surface multiples **(Figure 2)**. This additional illumination provides more reliable information about the quality and accuracy of the FWI velocity updates in the very shallow subsurface.

Each of the three components of the CWI workflow employs a different wavefield. Reflection tomography uses primary reflections only, whereas FWI utilizes the information captured by the very low frequencies in the refracted waves, and SWIM uses multiple reflections from the sea surface. SWIM gathers have been crucial in ensuring that the final velocity model is globally consistent and suitable for producing accurate depth images, from the shallow layers beneath the sea floor all the way down to deeper reservoir targets.

Putting it all together – A case study example from the North Sea

In 2009, the first 3D GeoStreamer survey in the North Sea was acquired over the Edvard Grieg, Johan Sverdrup and Luno fields in the southern part of the Utsira High in the Norwegian sector of the North Sea. The giant Johan Sverdrup discovery, made by Lundin and partners Statoil and Maersk Oil in 2010, is one of the five largest oil discoveries ever made on the Norwegian continental shelf **(Figure 3)**. The discovery in well 16/2-6 at Avaldsnes, on the south-eastern flank of the Utsira High, was followed by 30 appraisal wells including eight sidetracks in PL265, PL501 and PL502 (Blocks 16/2, 16/3 and 16/5).

The main reservoir at a depth of 1900 meters is composed of the Upper Jurassic Draupne sandstone dominated by coarse sandstones with average permeability in excess of 30 Darcies. The Avaldsnes High appears to play a key role in the distribution of the high quality reservoir sandstones up to a distance of more than 10 km from the paleo-shoreline. The reservoir is complex and the field represents a very challenging area for high resolution imaging. Accurate seismic-to-well depth ties are particularly critical, given that the reservoir is estimated to be less than 50m thick for much

VELOCITY DEPTH MODEL / Depth (m)

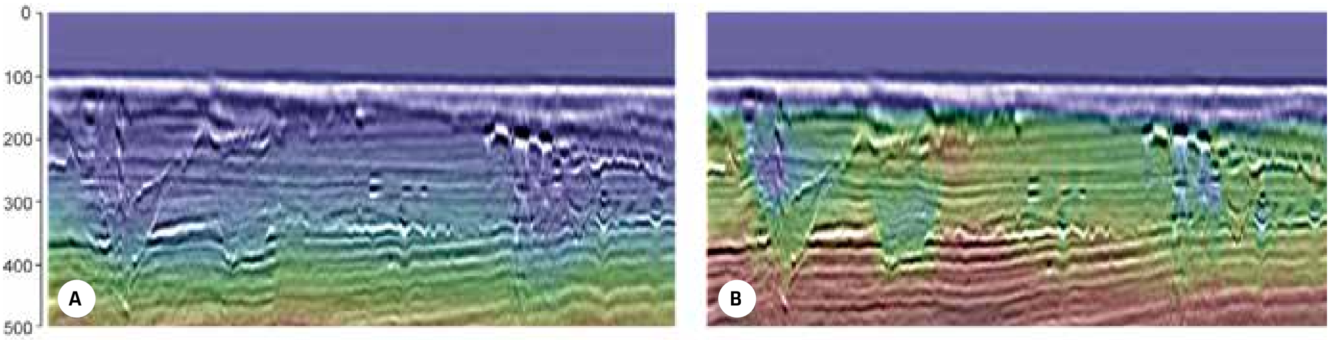


FIGURE 4: A) Wavelet shift tomography with the Kirchhoff depth migrated image overlaid **B)** FWI with Kirchhoff image overlaid. **Data:** Lundin

KIRCHOFF PSDM V SWIM / Depth (m)

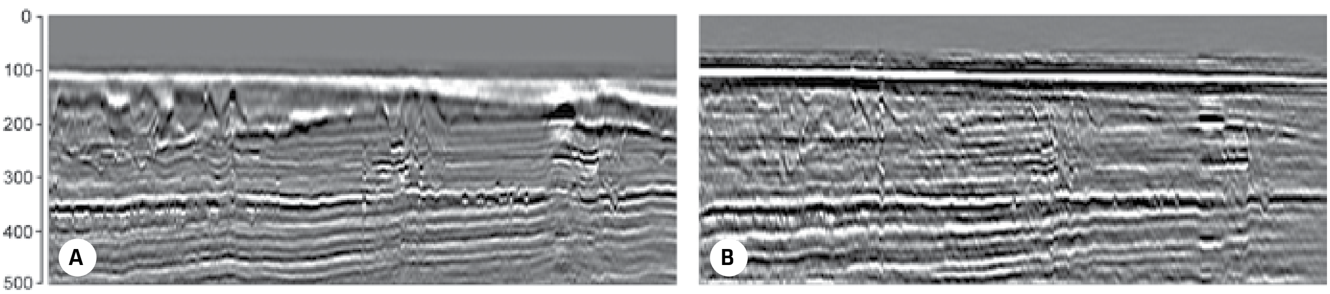


FIGURE 5: A) Traditional Kirchhoff PSDM of shallow overburden. **B)** SWIM depth image of the same shallow section. Notice improvements in the top section of the image and clearer deeper regions, due to improved illumination and increased fold. **Data:** Lundin

of the Johan Sverdrup discovery. Historically a variety of near-surface velocity anomalies would have made this impossible. Improving reservoir delineation and solving depth conversion problems were essential steps during the field appraisal.

The asset team therefore launched a new pre-stack depth imaging project, using the existing broadband dual-sensor towed streamer data, with the objective of creating a velocity model that would accurately account for small scale heterogeneous near-surface velocity variations. A pre-existing velocity model built on older, conventional 3D seismic data was used as the starting point to speed up the process. However, due to the shallow water depth (85-115m) in the survey area, conventional reflection tomography on the legacy project had failed to produce a sufficiently accurate shallow overburden model. To avoid possible instabilities in the later application of FWI, reflection tomography was applied to the GeoStreamer data, to improve the initial velocity model with particular focus on a more precise estimation of both velocities and the laterally-consistent anisotropy parameters in the shallow overburden. These velocity updates provided a much improved match between modelled and observed refraction data, permitting the subsequent FWI updates to resolve additional high-resolution velocity variations associated with channels, pockmarks and gas chimneys in the shallow overburden **(Figure 4)**.

SWIM angle gathers were used to validate the longer wavelength features of the updated velocity model. These are not easy to observe or cross-check in the data domain using FWI. The additional illumination achieved by imaging both primary and multiple wavefields provided a significantly enhanced higher resolution shallow overburden image **(Figure 5)**. This was of particular importance as a shallow wedge covers large parts of the field **(Figure 6)**. The long wavelength velocity variations associated with this wedge structure have a significant impact on the vertical position of the target sands in respect to the oil-water contact. For the deeper part of the overburden, particularly the chalk layer and the target zone, high-resolution Reflection Tomography was applied. Significant

SWIM WITH FWI

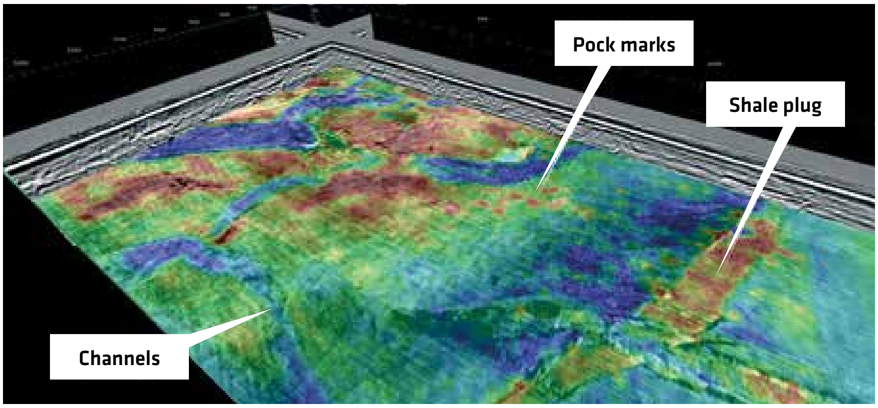


FIGURE 6: SWIM image at 250 m depth with FWI velocity model overlaid. Shallow channels, pockmarks, shallow gas and a relatively large shale plug can be reliably identified. **Data:** Lundin

JOHAN SVERDRUP – RESERVOIR HORIZONS

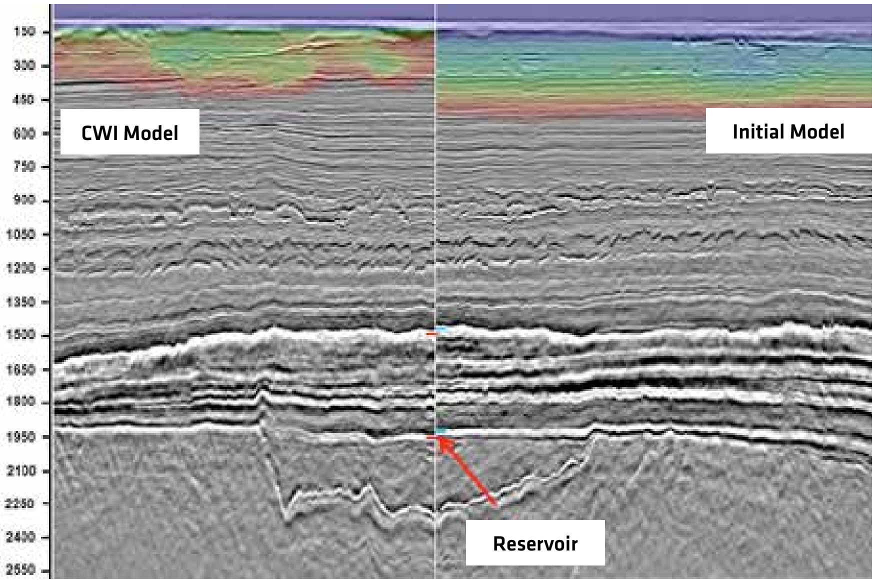


FIGURE 7: Substantial depth shifts apparent on the CWI model are highlighted at a virtual well location, suggesting a much improved match with the reservoir horizons at various well locations in the area. **Data:** Lundin

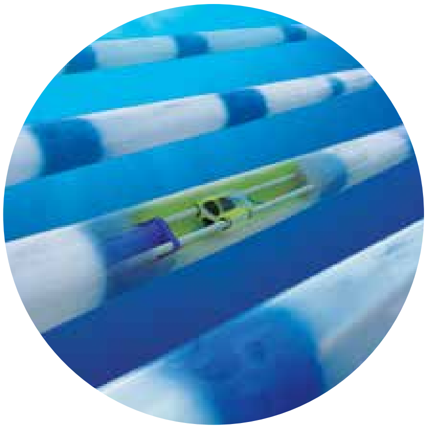
improvements were made in the quality of the final high-resolution subsurface image compared to the legacy PSDM data, and the combined project objectives of improved reservoir delineation and seismic-to-well depth ties were thus achieved.

Knowing the shallow brings the deep into focus

Oil companies require a very accurate and reliable structural image of the reservoir. Producing such an image using seismic data requires detailed knowledge of the propagation speed of sound in all the rocks overlaying the reservoir. Estimating velocity information in the very shallow section of the overburden, closest to the ocean floor, is especially challenging – particularly in areas of relatively shallow water. Any errors in estimating the propagation speed of seismic waves in the near surface will lead to significant uncertainties in the position and shape of the reservoir structure at depth.

There is another good reason for requiring an accurate picture of the sub-surface from shallow to deep. A more detailed image of the rocks at or close to the seabed can help oil companies to place seafloor equipment, identifying potential hazards and avoiding structural changes which may result in the opening of faults and fractures during production.

So no matter how deep the targets, to improve the reliability of reservoir estimates and reduce risk of finding and producing them, CWI provides a very useful addition to the reservoir imaging toolbox. ●



ONE STEP CLOSER TO **REALITY**

USING GEOSTREAMER TO DERISK EXPLORATION

As exploration risk steadily increases and return on capital employed gets squeezed, investors should demand seismic technologies that can reduce the likelihood of failed wells before placing the drill bit.

Text Andrew Long **Illustrations** PGS

IHS statistics reveal that the 2013 global oil discovery rate was about 13 billion barrels (Bbbl), the lowest since 1952. New field sizes are on a slow, downward trend for both conventional and unconventional oil and gas. Deepwater has accounted for 50% of all conventional discoveries over the past four years. Of major concern to our industry, average return on capital employed has fallen to about 15% from about 30% a decade ago. Such considerations have understandably encouraged the growth of activity in shale gas and tight gas exploration in the US and elsewhere around the world. In all areas, the requirements to reduce environmental exposure are steadily increasing, to minimize seismic activity in sensitive areas, drill fewer unnecessary exploration wells, manage infrastructure better, and so on. Consequently, there is more incentive to "get it right the first time". Seismic surveys and the management of exploration and appraisal drilling programs are increasingly under the microscope. Unfortunately, seismic imaging still creates too many false leads. Reservoir delineation is often too ambiguous in immature exploration areas, and far too much dependency is left to expensive drilling efforts to validate or invalidate possible prospects identified on seismic data. Quite simply, exploration risk is steadily increasing, so seismic technologies that reduce the likelihood of failed wells have obvious value.

This has fostered a wave of broadband seismic solutions that yield stack images with improved textural character, revealing more of the Earth's response and improving general interpretation confidence. While most of the broadband options improve the clarity of the strata, very few can help to quantify the volume of hydrocarbons. Only the best are applicable to seismic inversion studies – the analysis of angle-dependent amplitude content in pre-stack seismic data that can lead to quantitatively accurate predictions of reservoir rock and fluid properties.

Figure 1 shows an anticlinal reservoir at the Jurassic level in the North Sea. Although conventional hydrophone-only streamer data yield seismic images capable of delineating the prospect structure, pre-stack inversion of the amplitude content reveals a patchy and ambiguous expression of possible hydrocarbon distribution. When the elastic attributes derived from seismic inversion are extracted from a 3D subset immediately surrounding the reservoir and cross-plotted, in an effort to identify lithology and fluid content, two features are immediately obvious: 1. The background trend is quite flat and is a bad fit to the trends expected from the intersecting well log data, and 2. There is significant overlap between different lithologies – their discrimination based upon the elastic attributes will therefore be highly ambiguous. In contrast, the results derived from GeoStreamer data are striking. The expression of the hydrocarbon signature is uniform across the anticline, matching the hydrocarbon column intersected by the two well locations. Furthermore, the background trend on the cross-plot accurately follows the trend from the well data, the separation between different lithologies is more distinct, and there is a tight correlation between the well and seismic attributes corresponding to each lithology.

Be wise before the drill bit

What is remarkable is that the GeoStreamer "relative" seismic inversion used no well information. The result was achieved using only the pre-stack seismic data. Technically speaking, GeoStreamer has accurately preserved the angle-dependent amplitude expression of the reservoir rocks and fluids, and has also accurately preserved the frequency-dependent phase information in the seismic wavelet – especially for the ultra-low frequency amplitudes and phase where the greatest value to the seismic inversion exists.

At a superficial level, the GeoStreamer results unambiguously confirm the location of a hydrocarbon-filled reservoir, whereas the prospect was very uncertain on conventional streamer data. **Figure 2** shows the next level of confidence that can be derived in the "derisking" of this field – quantifying the volumes of hydrocarbons in place.

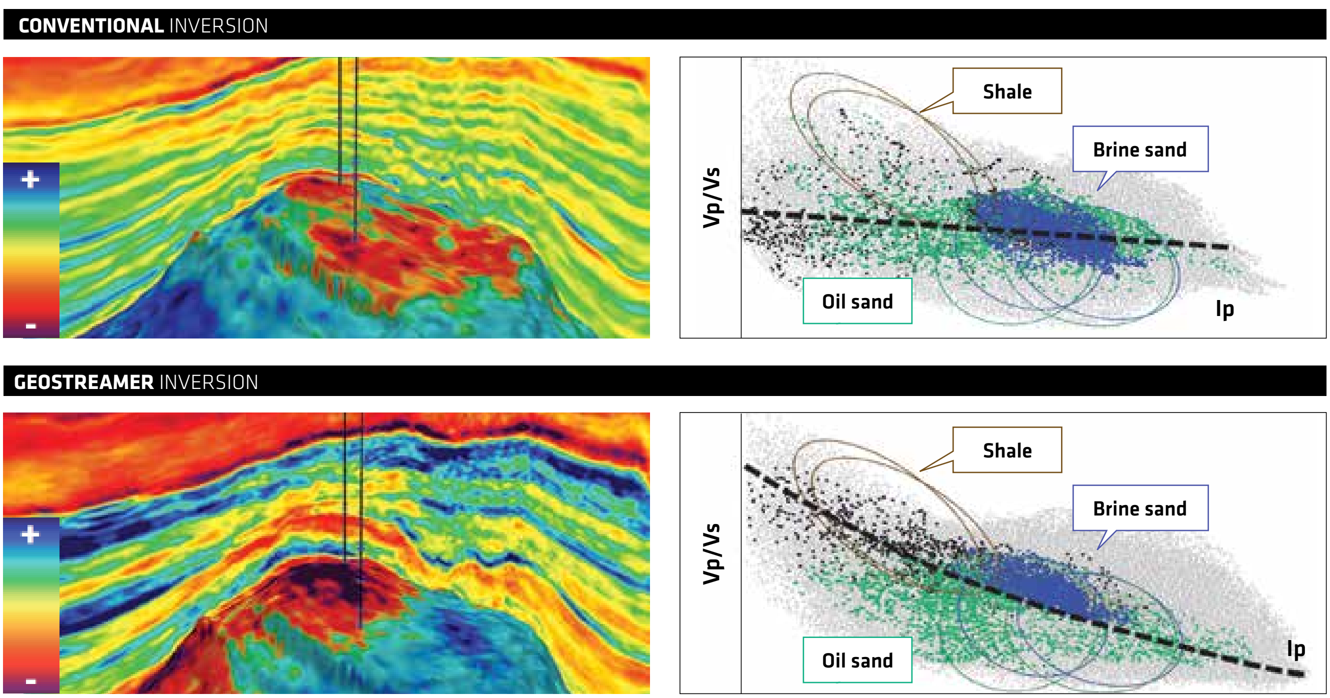


FIGURE 1: Seismic inversion of GeoStreamer data (lower panel) reveals an unambiguous indication of hydrocarbons; both in terms of the impedance image and in terms of cross-plotted elastic attributes. In contrast, seismic inversion of conventional streamer data (upper panel) fails to identify the presence of hydrocarbons or the background lithology trend in the reservoir structure. Vp/Vs = the ratio of compressional and shear velocity in the reservoir, Ip = acoustic impedance (also the color scale on the images). The dashed line on the right plots is the background trend; correctly identifiable on the GeoStreamer data. No low frequency model was used in either inversion.

PROBABILITY OF OIL SAND DISTRIBUTION

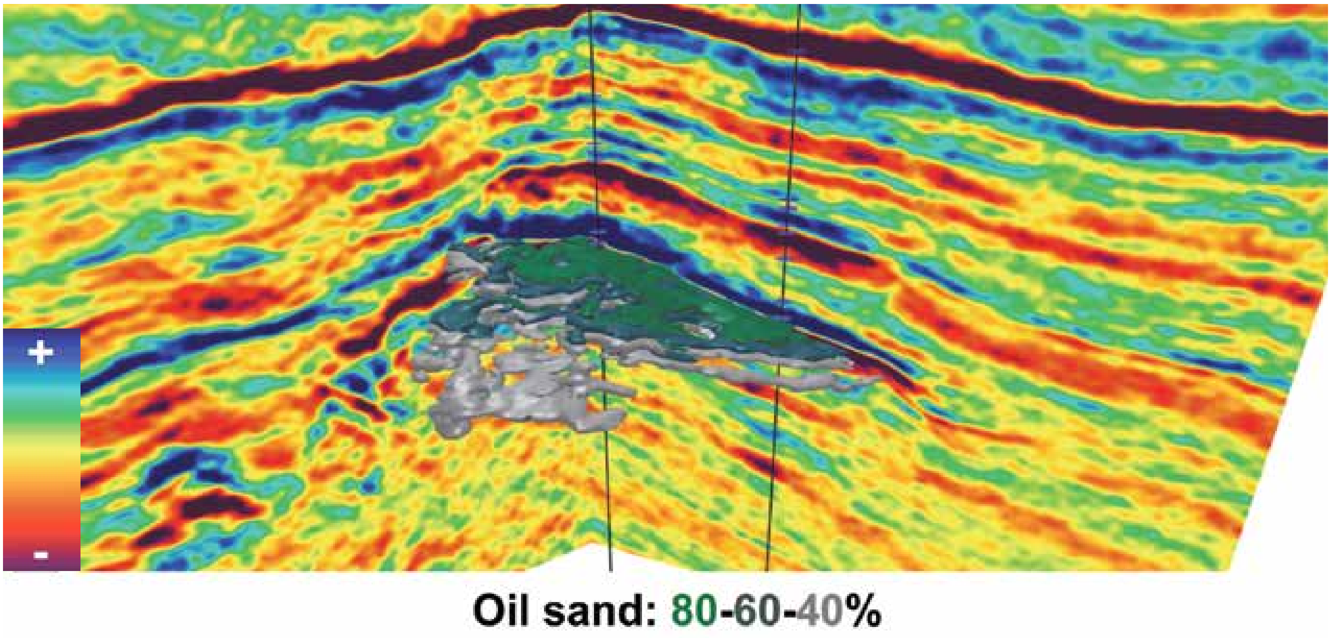


FIGURE 2: Predicted spatial extent of oil saturated reservoir rocks with varying probabilities based upon the results in Figure 1 calibrated by rock physics analysis.

With the assistance of complementary rock physics trend analysis, the elastic attributes from seismic inversion of GeoStreamer data are used to predict the spatial probability that the reservoir is saturated with varying degrees of confidence. For example, a larger volume can be mapped with 40% probability of being oil-filled than can be mapped with 80% probability of being oil-filled. The ability to identify the spatial extent of a reservoir with various probabilistic hydrocarbon scenarios is a key outcome for an oil company with several identified leads and prospects. Different drilling candidates can be ranked and prioritized. Likely reserves in place and recoverable reserves can be determined for commercial planning of investment scenarios. Such endeavors are only feasible, however, if the associated quantitative seismic analysis is robust and reliable in different geological settings.

Another key consideration in the pursuits shown in **Figures 1** and **2** is that the quantitative interpretation (QI) exercise is as data-driven as possible, with as little model-driven input as possible.

Historically, seismic inversion relied upon significant low frequency model building – compensating for missing, ultra-low frequency, amplitude information by building coarse background trends from interpreted models to guide the interpolation of available well log data. Although well data is precise at the well location, it rapidly becomes invalid away from the well. Ideally, the high resolution 3D spatial information in seismic data will exist over all frequencies of interest, particularly in the ultra-low frequency range of about 0-8 Hz typically missing from conventional streamer seismic data. Advances in GeoStreamer data processing have closed the majority of the low frequency gap.

Pre-salt exploration has a high industry profile because of the enormous stakes involved – potentially massive undiscovered reserves, confronted by massive drilling and exploration costs, using often poor seismic images, and often without the additional value provided by QI in non-salt provinces. Consequently, the exploration risks are huge. Even the largest oil companies can quickly extinguish their budget and shareholder patience with two or three failed drilling efforts.

Figure 3 shows a pre-salt example from the Campos Basin in offshore Brazil. Again, the GeoStreamer seismic image provides interpretation confidence, despite the obviously complex salt morphologies overlying the pre-salt prospects. This interpretation confidence is further reinforced by images of acoustic impedance; the outcome of pre-stack seismic inversion. Furthermore, **Figure 3** shows that seismic inversion using only the GeoStreamer data unambiguously identifies a large oil-saturated reservoir verified by an intersecting well. From a derisking perspective, **Figures 1 to 3** illustrate that GeoStreamer contributes in a quantitative and verifiable manner to the derisking of prospect identification and evaluation – in even the most challenging geological settings for seismic imaging and characterization.

Overall, derisking of hydrocarbon prospects via the seismic inversion of GeoStreamer data involves the accumulated contribution from several probabilistic workflows. This includes extracting seismic wavelets based upon statistical (Bayesian) schemes, rock physics analysis based upon the description of lithology and fluid properties as probability density functions, and the associated prediction of reservoir lithology and fluid distributions with statistical levels of uncertainty. Each consideration is too technical to discuss here, but the point is that the science behind GeoStreamer data analysis is as important as the GeoStreamer technology itself – a wealth of experience developed over seven years of global application, with tools and workflows built upon countless trials and case studies. Less uncertainty in how to apply GeoStreamer data translates to less exploration risk for our customers.

Furthermore, the recently commercialized PGS Towed Streamer EM technology can be simultaneously recorded with GeoStreamer data, providing electromagnetic data as a valuable complement to seismic data in a spatially-coincident manner. Together these data predict more reliable rock properties and will even more accurately predict hydrocarbons in place. Whilst low saturation gas is historically difficult to quantify using seismic inversion, EM data can be quite robust as a tool to quantify gas saturation. New PGS workflows quantify net-to-gross ratios and total hydrocarbons in place – with probabilistic uncertainties included. Technologies such as these should assist improved block evaluation, better drilling decisions, improved discovery ratios, more efficient production and higher recovery factors. ●

QI EXAMPLE FROM BRAZIL

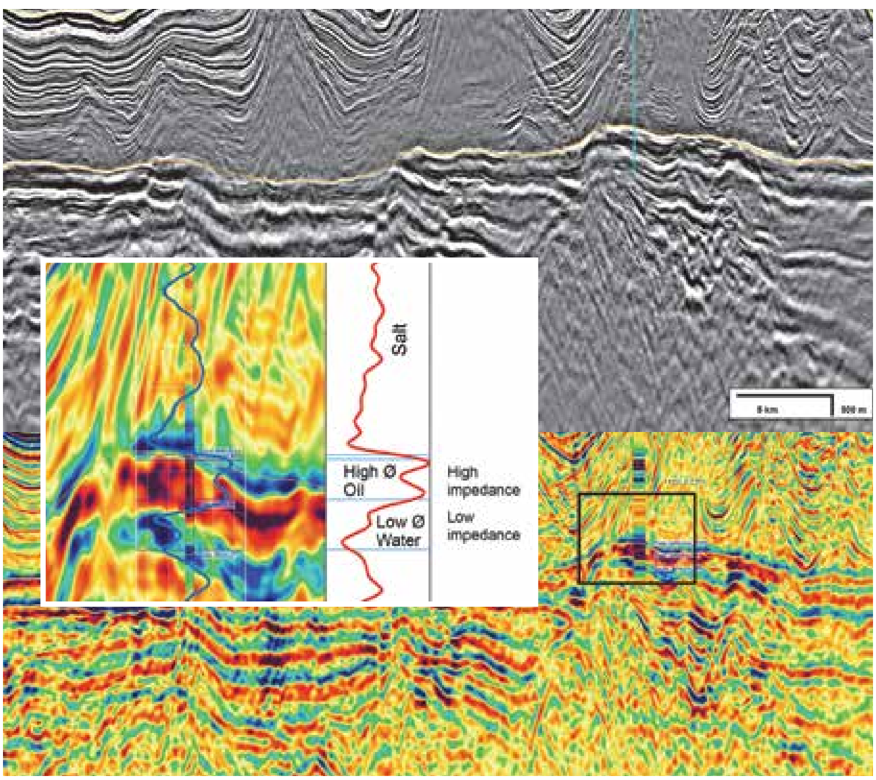


FIGURE 3: Pre-salt QI example from offshore Brazil. The GeoStreamer data in the upper panel were used in "relative" seismic inversion, again without any low frequency model contribution, to yield the acoustic impedance result in the lower panel. Analysis of the reservoir intersected by a well reveals an unambiguous indication of high porosity oil-saturated rocks overlying low porosity water-saturated rocks (inset panel). The blue profile plotted through the reservoir is the acoustic impedance measured along the well, and the red profile on the right is the equivalent acoustic impedance profile inverted from GeoStreamer data – an excellent match!

THE RISKS OF UNCERTAINTY

Risk management of health, safety and environment is a well-established tenant of operation, but what about Q? Can we take a risk-based approach to quality?

Text Pamela Risan **Illustration** Patrick Hardin, Cartoonstock **Photo** Nadia Frantsen

LUCK SELDOM HAS ANYTHING TO DO WITH IT

JOANNA OUSTAD

Over time, our focus on health and safety has delivered risk management appraisal systems and behaviors that have engrained them. A few years ago our HSEQ team spent all their time working with matters related to physical environment. Today that has shrunk to around 50% of our investigations. The same systems are being applied to other undesirable incidents and project outcomes. Although a broken leg cannot be compared to a broken streamer, both can be avoided by planning properly, analyzing risk and identifying mitigation measures. Investigations of underperforming projects can help us avoid repeating mistakes, which is good for us and for our clients.

The role of chance

PGS delivers reliable seismic projects not because of good luck but because we put a lot of planning and effort into it, claims Joanna Oustad, Senior Vice President Health, Safety, Environment and Quality. After several years as an HSEQ consultant for large oil and gas companies she joined PGS almost ten years ago, and is committed to delivering a clear message. For although we know that good planning is the key, it can still be tempting to put the occasional difficulty down to bad luck, but luck seldom has anything to do with it.

Operators and contractors have worked hard to improve safety, and now we are using the same methods to analyze root causes and evolve systems that evaluate and mitigate risks. We have evolved new behaviors and systems to institutionalize this approach. We are locked into an ambition of continuous improvement.

Today, industry standards for performance are high and increasing. Yet despite our unequivocal focus, accidents and incidents still occur. As we drive down the frequency of incidents and tighten our grip on the tools and training required to carry out projects, other dangers become apparent. "We saw that all the departments involved in a project need to share a common culture, avoiding the silos that so easily develop within big companies," says Oustad. Commercial and project delivery risks have become a new focus for action. So too has the recognition that we need to plan for failure of the mitigation measures.

"You also need a plan for what you are going to do if "Plan A" fails, and you need to acknowledge that sometimes that might not work either. How do you then recover? What if our controls fail, what do we do then?"

"Analyzing the landscape of risk is the key," she says. Various statistical probability measures are employed to assess exposure. Risks can appear from an approaching storm at sea but they can also be spawned by adjustments in project parameters, or new technology. Changing the specification, timing, circumstances, or budget for a project may alter the parameters in the field. One of the lessons we have learned over recent years is that we need to extend ownership of the risk picture further up the value chain. It starts way before the toolbox meeting. The tentacles of risk stretch into the offices of the sales team, the procurement manager and the CEO, even the Board of Directors. How will a yard stay or a frontier

location with unknown currents and coastlines affect us? These risks can also be mitigated, as long as we recognize that they are there.

New horizons

Thanks to new technology we can now search for and produce oil deeper, farther from shore and in harsher climates. That creates new challenges that we have not faced before. Our risk models for remote and sensitive areas may be based on fewer experiences than known producing fairways. That can mean we are more open-minded in considering what may go wrong, rather than naively assuming that experience elsewhere can be directly applied without further investigation.

Oustad suggests that a vital step is expanding the concept of HSEQ and risk management. "It covers everything, not just health, safety, environment and security but once we include quality we also encompass operational, technical and financial risk," she says. She sketches out the new landscape of risk management covering project parameters, operations and job-related safety. Each target area is owned by a different part of the organization. Each of them needs to assess the landscape, the conditions for success and failure, their own experience, plus intelligence gathered from elsewhere in the industry. The IAGC maintains a database of incidents going back to 1968 and including more than just geophysical contractors.

Change focus & perspective

In a business like ours, the fleet is a large part of the risk landscape, both in terms of exposure and consequence. Vessel management covers technology, crewing, and maritime maintenance; long-term trends that affect the project team. Projects mesh into this like gear wheels. Each one requires an ongoing assessment of the parameters, the environment, and the daily operations when the project is live.

"HSEQ today is about perspective. You've got to step up to see the detail and step back to see the bigger picture, then fly back to see the wider trend." Evaluating how parameters or changes influence other stakeholders in the operation and sharing information about any changes is essential. "Everyone needs to be aware what risk means and absorb it into their bone marrow. Risk thinking has become a central part of our culture."

Oustad's job is to predict the bad black swans before they appear. "You cannot always predict the catalyst but you can analyze the landscape to identify areas of vulnerability," she acknowledges. "It is important to perform investigations: analyze past failures and write reports," she says. "But it's not enough. We need to be better at predicting risk without the benefit of experience."

Oustad is in no doubt as to the relevance and value of this effort. "Better risk management means reduced incident frequency. That means safer operations. It also improves project success. If the project comes out as expected without proper quality management in place, you just got lucky. You can't run a business like that." ●

GLOSSARY

of technical terms

A

Abel prize Named after Niels Henrik Abel (1802–1829), the prize was established in 2001 by the Government of Norway. It comes with a monetary award of NOK 6 million (USD 1 million). PGS supports the work of the Abel Committee through its sponsorship of the Norwegian Academy of Science and Letters.

Acoustic impedance The propagation of a sound wave varies depending on the product of density of the material through which it is traveling and velocity of the seismic wave. The difference in acoustic impedance between rock layers affects the strength of the wavefield which is reflected back towards the surface.

Angle gathers A collection of seismic recordings (or traces) from a common surface location that are represented by a range of subsurface reflection angles, each trace having the same reflection angle at all depths.

Anisotropy Having physical properties that differ according to the direction of measurement. In seismic it is used to describe the directional dependence of the velocity of seismic waves in a given medium or rock type.

Anticlinal reservoir An anticline is an upwardly-convex, arch-shaped fold in the layers of the Earth. Many excellent hydrocarbon traps, occur within anticlines with reservoir-quality rocks in their center and impermeable seals in the outer layers of the fold.

B

Black swan theory A metaphor that describes an event that comes as a surprise, has a major effect, and is often inappropriately rationalized after the fact with the benefit of hindsight. The theory was developed by Nassim Nicholas Taleb

Broadband seismic Seismic signals which contain a range of frequencies significantly higher than normal both at high and low frequencies.

C

Chaos Complete confusion and disorder, with no immediate view of achieving stability. Total unpredictability is often considered as chaos. In deterministic chaos the chaotic behavior stems from the fact that the system is sensitively dependent on its initial state. Popular science refers to this as the butterfly effect.

Complete Wavefield Imaging (CWI) A logical workflow pioneered by PGS using every type of seismic wavefield recorded by the GeoStreamer platform: primary reflections, refractions and multiples.

D

Dual-sensor streamer Marine seimic device that records both p-waves and particle velocity.

Dynamical systems Mathematical concept where a fixed rule describes the time dependence of a point in a geometrical space. Examples include the mathematical models that describe the swinging of a clock pendulum, the flow of water in a pipe, and the number of fish each springtime in a lake.

E

Elastic properties The mechanical properties of rocks. Elasticity describes the relationship between stress, (the action of a force) and strain (the deformation of the material under stress).

Elastic attributes Three seismic properties, P-wave velocity, S-wave velocity, and density (if established), are the key elastic attributes used by geophysicists to understand the elastic properties of rocks and fluids.

F

Full Waveform Inversion (FWI) A sophisticated computational solution that iteratively reconciles synthetic versions of each shot gather (the fundamental seismic recording at each surface location) with the real data. When the two versions are comparable, a remarkably high resolution model of the P-wave velocity in the Earth is achieved. FWI is increasingly used to yield more accurate seismic images of the Earth, and benefits in particular from the stronger low frequency signals delivered by GeoStreamer.

G

GeoStreamer A dual sensor broadband acquisition technology that permits wavefield separation, enabling imaging with multiple energy as well as primaries.

H

Hydrocarbon signature
A tell-tale expression of hydrocarbons in seismic data that can be identified by an experienced geophysicist. More common with GeoStreamer data.

K

Kirchhoff migration
The most common method of seismic migration.

M

Multiples
Seismic wavefields that have made the journey from the surface to any geological target and then back to the surface in any kind of indirect manner involving reverberations between various geological layers.

P

Primaries
Seismic wavefields that have made a direct journey from the surface to each geological layer and then back to the surface, without any reverberations between various geological layers.

PSDM Pre-stack depth migration, the preferred implementation of seismic migration that most correctly represents the spatial geometry and vertical depth of the subsurface geology.

Q

Quantitative interpretation (QI) A generic term that describes various workflows for deriving elastic rock and fluid properties from seismic data. The best known QI approach is seismic inversion.

R

Reflection tomography An iterative computational approach that reconciles the recorded time of each seismic reflection event with the times predicted from a velocity model. When the synthetic and real data match to an acceptable degree, the velocity model is assumed to be reasonably correct. A more sophisticated alternative is FWI.

Rock properties
The physical characteristics of rocks commonly described in terms of the elastic attributes derived from seismic data and QI.

S

Seismic Inversion
An iterative computational process that converts the observed reflection angle-dependent amplitudes of seismic data (preferably pre-stack), to an elastic model of the Earth using theoretical predictions from classical physics of elasticity.

Stacking Adding seismic traces together from complementary records to reduce noise and improve data quality.

Separated Wavefield Imaging (SWIM)
A method whereby multiples are used to produce seismic images that offer complementary information to conventional seismic migration using primary reflections.

V

Velocity anomalies
Geophysicists evaluate models of velocity variations in the Earth in order to create reliable seismic images.

Velocity model
A model of the Earth derived by geophysicists, where the property of interest is typically the local (or interval) P-wave velocity at each point in the Earth.

LET US **KNOW**

If you would like to suggest any additional terms for the glossary, please feel free to contact us at info@pgs.com

IN THIS ISSUE

THE UNCERTAINTY OF
LIFE AND SCIENCE

Managing Uncertainty
Black swans are events that appear out of nowhere and disrupt the established order. Afterwards many people will claim they were all too predictable. The key to managing uncertain conditions often lies in framing the question correctly.

FEATHER
IN YOUR CAP
If you can't predict the catalyst, you can analyze the landscape to spot vulnerabilities.

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