Delphi Consortium

Strategic fundamental research for the geophysical industry

Oktober 2015

Creating value with science

Delphi Introduction

1

New concepts are needed to secure future energy supply at affordable prices

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Introduction

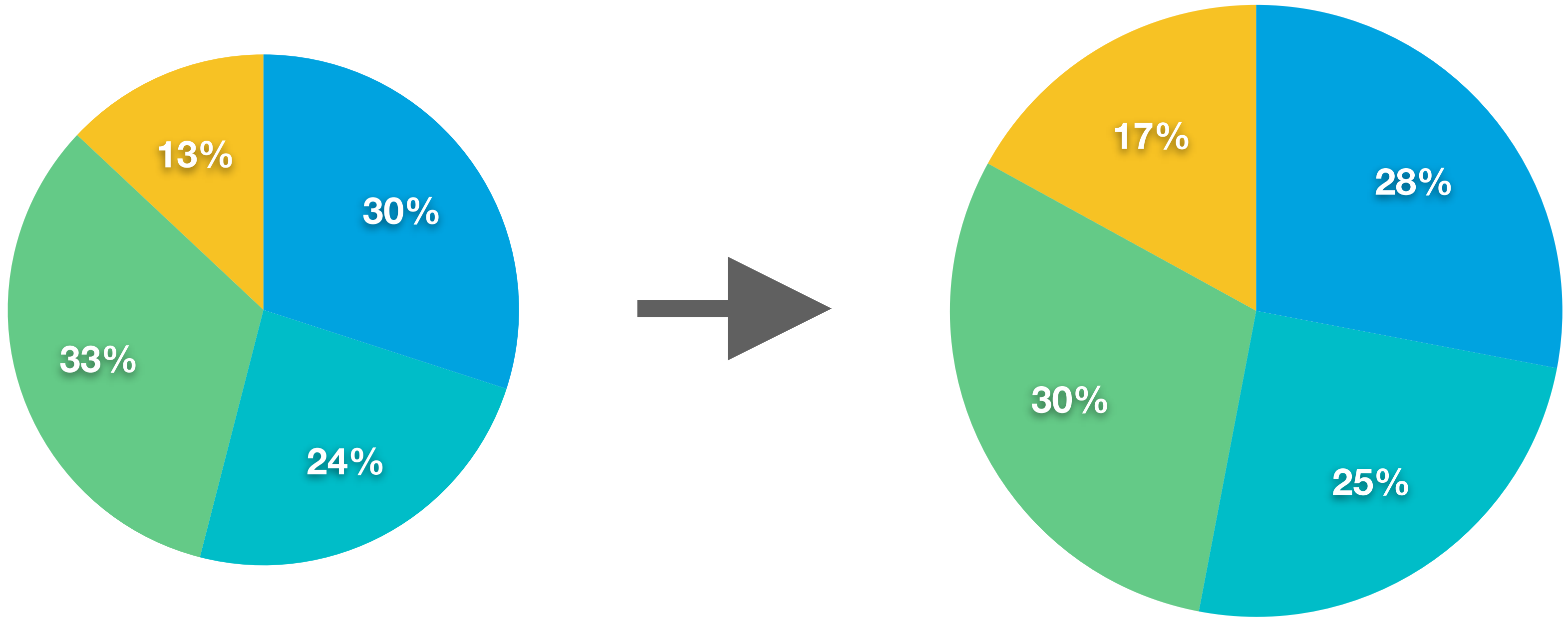
Looking at the ongoing increase of the world's population, together with the continuous growth of the global economy, the need for energy will continuously rise (see **Figure 1-1**). It is expected that in 2025 the world will use 23% more energy than in 2013. An issue of great concern is that in 2025 the contribution of non-fossil fuels may still not exceed 20%. This means that the upstream oil and gas industry will face an enormous challenge to increase capacity and replace reserves (see **Figure 1-2**). Here, priorities are improved technology portfolios and better cross-disciplinary skills in the professional workforce.

Through the years, geophysics has become a critical technology in the upstream oil & gas business (exploration and production), allowing detailed visualization of the reservoir properties of new prospects and existing fields in complex areas. To meet the challenge of capacity and reserves, the oil industry need to improve its geophysical acquisition, imaging and characterization capability far beyond current limits. This challenge become even larger nowadays, as with low oil prices several fields may end up below their break-even point (see **Figure 1-3**). Therefore, high-technology solutions for enhanced oil recovery and more accurate seismic monitoring is a must in the coming years.

The mission of the Delphi consortium is to give a significant contribution to the realization of these ambitions.

A unique property of Delphi is that scientific results are formulated at different levels of abstraction. This has the advantage that at the Delphi meetings communication between researchers and sponsors occurs largely at a conceptual level, containing the essentials only. At lower levels, increasingly more theoretical detail is visible. These details are reported in the Delphi proceedings. The lowest level represents the Delphi software, containing all required detail needed for application at the sponsor's site (www.delphi-consortium.com). In addition, another unique aspects is that the research activities within the Delphi consortium span the full upstream cycle from data acquisition towards reservoir monitoring and characterization and beyond, making a link with the reservoir engineers (see Chapter 3).

Introduction



Year 2013: Total world energy consumption is 505 quadrillion BTU

Year 2025: Total expected world energy consumption is 623 quadrillion BTU

● Coal ● Gas ● Oil ● Nonfossil

Figure 1 - 1: World energy consumption in 2013 and the predicted consumption in 2025, showing the different fuel types. Shale oil & gas will be the big game changer.

Introduction

Exhibit 8: Marginal Top 360 oil fields require US$100/bl+ oil price
Breakeven of non-producing and recently onstream oil assets

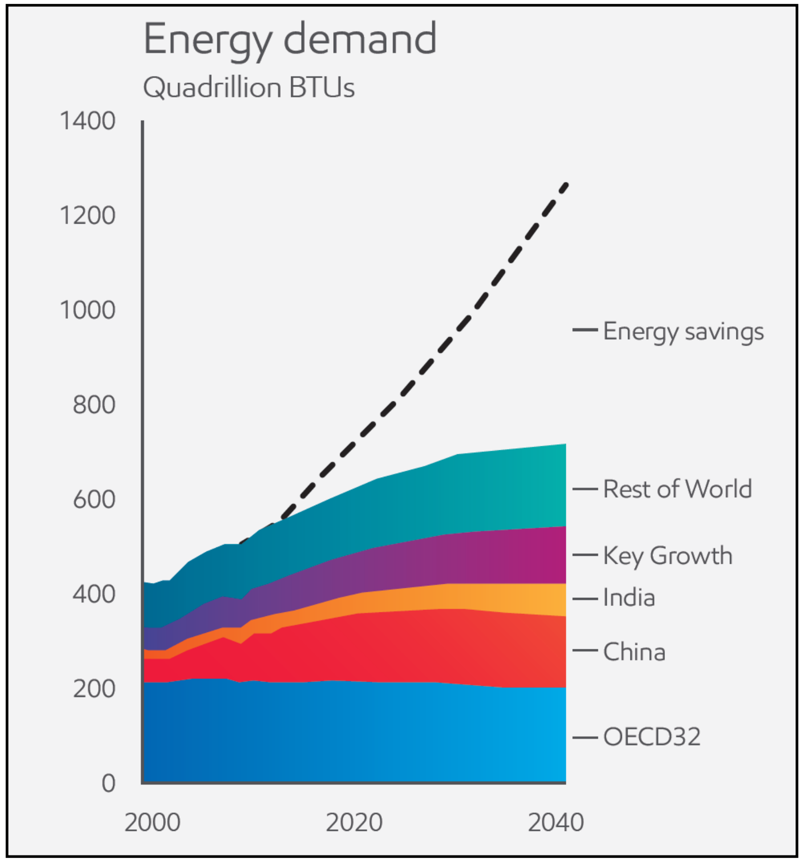


Figure 1 - 2: Energy demand per group of countries. (Source: The outlook of Energy, 2015, ExxonMobil).

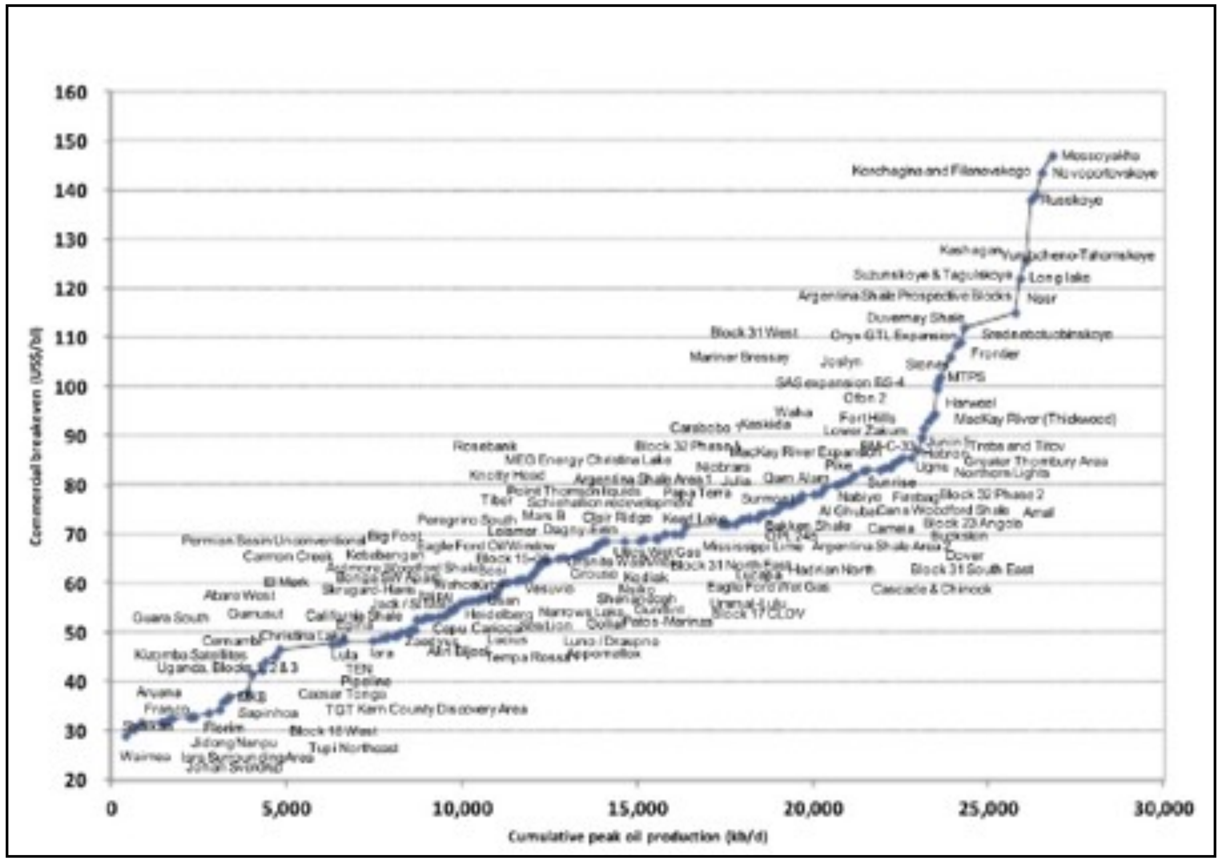


Figure 1 - 3: Breakeven price for top 360 oil fields. (Source: http://peakoil.com/production/goldman-sachs-360-projects-to-change-the-world).

Role of consortium research

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To increase the pace of innovation, science and business must interact more than ever before. In Delphi, strategic fundamental science is directed to problems and opportunities that are shared by all companies in the consortium.

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Role of consortium research

In the past, both universities and industrial laboratories have invested extensively in the generation of new scientific knowledge to fulfill the business needs. Experience shows, however, that new scientific results are often presented in such a way that the path leading to practical application is very time consuming. Therefore, in the last decade the need of a more effective and faster innovation path - leading from fundamental science to profitable business - is being emphasized. Here, technology (‘know-how’) is an essential link. The emphasis of establishing science-based technology platforms is visible in all sectors of industry; this is particularly true for the capital intensive upstream energy sector. Because practical problems never behave in a disciplinary way, science-based technological research must be cross disciplinary.

Today, there is little room for fundamental scientific research inside companies. Fundamental science is outsourced to universi- ties and national laboratories. This development emphasizes the importance of a fruitful collaboration between the academic community and the industry.

From the above it follows that industry-sponsored academic research should be guided by three principles:

1. Focus scientific programs on the emerging problems and opportunities that are shared by the entire industry;
2. Aim at cross-disciplinary research programs for new directions in enabling technology;
3. Make technology transfer an important part of the research activities, utilizing cyclic interaction.

This means that the interaction between academic researchers and industry members need be frequent and intense. In the Delphi consortium discipline-crossing communication, based on feed-forward and feed-back (cyclic concept), has high priority. Scientists and sponsors meet at least twice a year, once in Europe and once in the USA. In between, work visits are organized. Actually, the Delphi consortium functions as a dynamic network, supported by a protected website

Principle of the Seismic Value Chain

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In network organizations, work processes do not follow simple linear paths but they occur in a cyclic manner with feed-forward and feed-back paths. The result is integration along traditional organizational boundaries.

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Principle of the Seismic Value Chain

In network organizations, interaction processes in workflows do not follow simple linear paths but they occur in a cyclic manner with feed-forward and feedback paths (Senge, 1990; Berkhout, 2000). In this cyclic concept, the process model consists of coupled loops and the organization that facilitates the information flow in those loops is flat with short interconnections. Cyclic interaction applies to the E&P workflow in the widest sense, but considering the research topics in the Delphi consortium, we will focus on the inner loops of geophysics only. **Figure 3 - 1** shows the Seismic Value Chain (SVC). It visualizes the cyclic interaction processes between the three disciplinary nodes: seismic acquisition, structural imaging and reservoir characterization.

Current research in Delft aims at extending the seismic value chain to the entire upstream workflow (E&P innovative circle), including geological modeling and reservoir management.

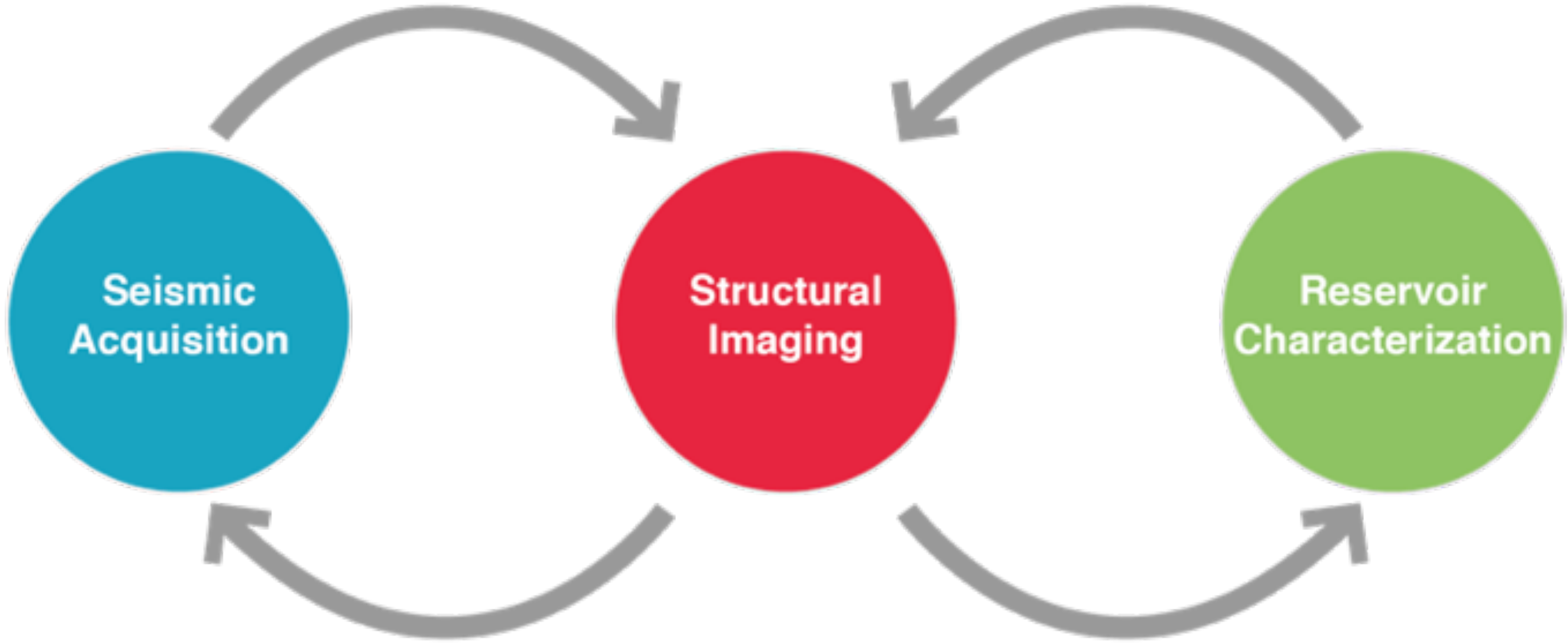

Figure 3 - 1: Cyclic interaction in the Seismic Value Chain (SVC), showing the importance of cross-disciplinary communication between the disciplinary seismic nodes. Bear in mind that the forward and backward information flow between the two inner loops, connecting acquisition and characterization, is described by a socio-technical lemniscate.

Principle of the Seismic Value Chain

In the double-loop seismic value chain the needs in reservoir characterization should drive structural imaging and the needs in structural imaging should drive seismic acquisition (double feedback). Moreover, new capabilities in acquisition should inspire new developments in the imaging node and new capabilities in imaging should inspire new developments in the characterization node (double feed-forward). Hence, both feed-forward and feed-back processes are required, defining the ‘context of discovery’ and the ‘context of justification’ respectively.

Note the important property that interaction is not only first order but also second order. This is the organizational architecture that we have established in the research program of the Delphi consortium, crossing also organizational boundaries within the Delft University (Berkhout, 2005).

If we look at seismic research today, the following strategic issues can be observed in the different nodes of the Seismic Value Chain:

1.Seismic acquisition node

The largest investments along the seismic value chain occur in data acquisition. Therefore, more knowledge is required how to design economical acquisition geometries (**node 1**) that potentially yield the best images in terms of spatial resolution and amplitude accuracy (**node 2**), as well as the best reservoir models that allow accurate estimates of recoverable reserves at any stage of the life cycle (**node 3**). A fundamental research question is to what extent sparse spatial sampling in acquisition can be compensated for by interpolation beyond aliasing (preprocessing in the acquisition node). Another important issue in node 1 is how preprocessing can properly solve the near surface problem in land and sea-bottom acquisition. Until today, ‘statics’ is still an unsolved problem. Note that if data-driven processing techniques such as wavelet deconvolution, primary-multiple separation, velocity estimation, and full wavefield imaging are going to play a more important role, data acquisition design need to gain significantly more attention.

The philosophy of the Delphi consortium is: ‘let the data speak’. We believe that too many of today’s solutions are biased by preconceived models, particularly in the second part of the value chain. Economizing on data acquisition may be penny-wise and pound-foolish. Recently, we emphasized the large advantages of blended acquisition, involving the utilization of incoherent wavefields. Furthermore, by decentralized acquisition systems with optimally spaced sources in dedicated frequency bands and with smart source coding in combination with utilizing all scattered energy, maximum information is obtained from our acquisition efforts.

Principle of the Seismic Value Chain

2.Structural imaging node

Until today, imaging requires primary reflection data. A lot of progress has been made on the removal of multiple scattering events. This is particularly true for multiples that cannot be easily distinguished from primaries with the aid of move-out. Here, the data driven approach of Delphi in terms of multi-record convolution (Berkhout, 1982) has shown excellent results in practice (Verschuur, 1991) and is now being used worldwide. 3D versions of the data-driven algorithm (SRME) are commercially available now. The current focus is solving the challenges with respect to strongly reverberating shallow water layers and internal multiples.

Similarly, a lot of progress has also been made on the development of seismic migration algorithms. However, the weakest point of today's migration technology is the estimation of accurate migration velocity models. For instance, imaging below salt is still a largely unsolved problem.
In the Delphi consortium, full wavefield migration is being developed, utilizing multiple scattering (surface and internal) as well. In addition, we believe that velocities should be derived by the migration process itself ('joint migration-inversion'). This topic is actively pursued in our research.

3.Reservoir characterization node

In reservoir characterization high-resolution seismic images, angle-dependent reflection information and accurate velocity models are needed to determine the volumetric properties of a (potential) field. In addition, using rock physics the internal micro properties of the reservoir need be estimated in terms of rock composition and pore properties. In reservoir characterization we aim at extracting these medium properties in an accurate manner via broadband, full waveform inversion. Delphi's joint migration-inversion technology provides the wavefields allowing localized full waveform inversion, which reduces the complexity of the inversion problem enormously.

The ambition in the characterization node is to make also use of borehole measurements and production data. The target is to obtain accurate estimates of saturation and stress by using an integrated estimation approach that combines 4D seismic inversion and production history matching in a geologically meaningful way.
In time-lapse seismic inversion, the double-loop interaction between seismic acquisition and reservoir characterization becomes very clear: repeated acquisition aims at monitoring changes in the reservoir – in terms of changes in saturation and stress – during the production phase. These changes drive the reservoir management decisions.

Principle of the Seismic Value Chain

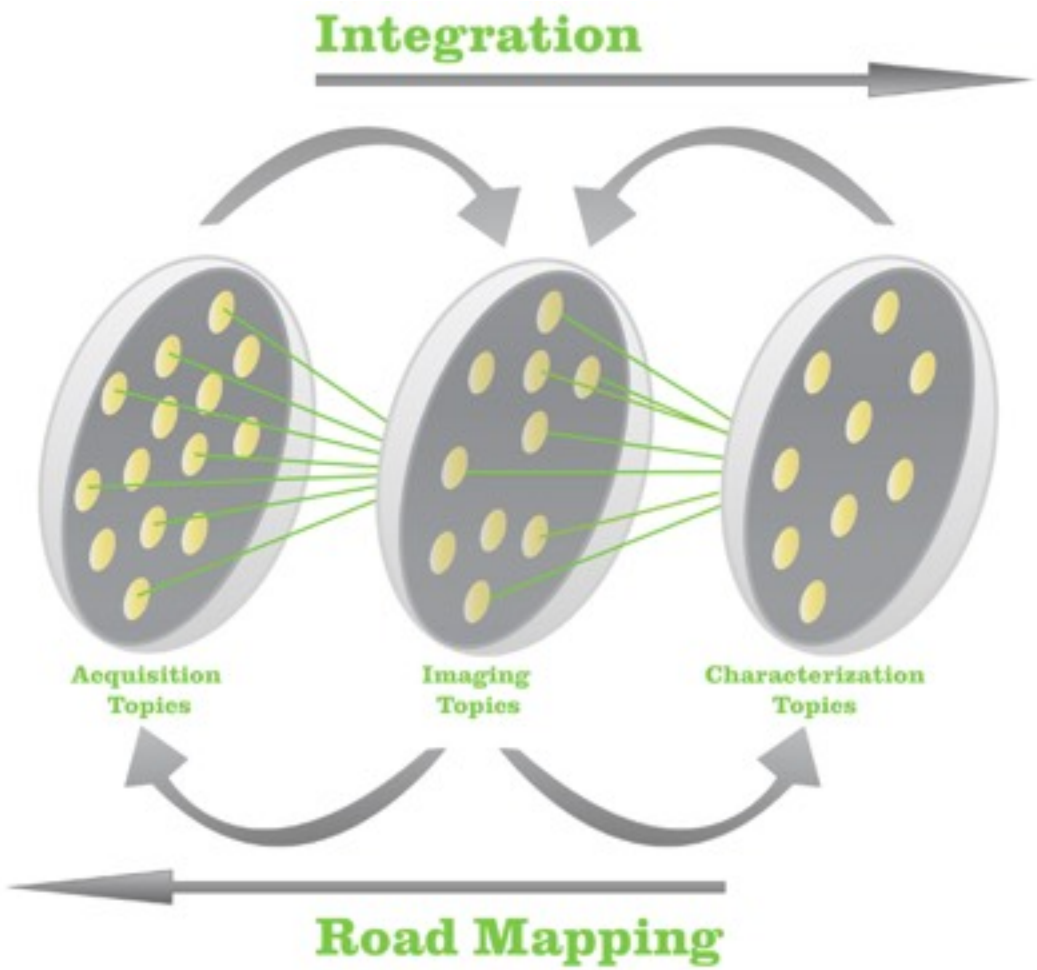

Figure 3 - 2: Seismic Value Chain at a more detailed level. In node 1 Delphi research topics are: acquisition design for both coherent and incoherent shooting, deblending algorithms, compensation for near surface distortion. In node 2 Delphi research topics are estimating multiple scattering, migration of primaries and multiples (FWM) and joint migration-inversion (JMI). And in node 3 Delphi research topics are JMI for borehole data, JMI in time-lapse applications, reservoir-oriented full waveform inversion (FWI-res) aiming at detailed reservoir changes in terms of hydrocarbon saturation and pore fill pressure by the use of seismic and (optionally) EM measurements, taking advantage of geologic prior knowledge.

In the Delphi strategy, seismic road mapping is an important concept to (re)set priorities: project targets are proposed by scientists as well as sponsors, starting at the end of the value chain and moving back into the chain from characterization via imaging to the acquisition node. Based on those discussions, projects are updated and revitalized.

In projects related to the exploration and appraisal phase, the static properties of the reservoir are of prime interest. Here, information requirements on recoverable reserves need to be the start of the road mapping process. In projects related to the development and production phase, the dynamic properties of the reservoir are of prime interest. Here, information requirements on pore properties and fluid flow within the reservoir need to be the start of the road mapping process (see **Figure 3 - 2**).

Background of Delphi

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Delphi started in 1982 with 5 companies. Today, there are 33 companies that finance the Delphi research program.

Delphi Consortium

Background of Delphi

Inspired by the success of John Claerbout's consortium at Stanford in the seventies, professor Berkhout decided in the early eighties to set up a seismic consortium at the Delft University of Technology (TU Delft). Particularly with the help of one of his students, Paul van Riel (co-founder of Jason Geosystems), he started in 1982 the so-called PRINCEPS-consortium. The objective was estimation of acoustic impedance from seismic data by constrained trace inversion. PRINCEPS started with 5 companies.

From the research in the PRINCEPS-consortium it became clear that the extraction of in-situ rock information beyond acoustic impedance would require analysis of pre-stack seismic data, preferably after removal of the overburden propagation effects. Therefore, it was decided to set up a second consortium in Delft that was aiming at distortion-free, angle-dependent input for PRINCEPS. Particularly with the help of Kees Wapenaar (who had just successfully completed his Ph.D. thesis), professor Berkhout founded in 1987 the so-called TRITON-consortium. The objective was target-oriented pre-stack migration, using multiple removal and true-amplitude redatuming as preprocessing steps. TRITON started with 13 companies.

From the inversion research in PRINCEPS and the migration research in TRITON it became readily clear that both consortia would significantly benefit from a closer interaction. In 1989 it was decided to merge PRINCEPS and TRITON into one consortium: Delphi. The objective of Delphi was an integrated approach to multiple removal, pre-stack migration and reservoir characterization. Delphi started with 21 companies.

From the integrated research in Delphi it emerged that the success of seismic imaging is largely determined by the way data acquisition is carried out. This particularly applies to the geometry of the sources and the detectors. Therefore, it was decided to start a third initiative aiming for an acquisition consortium that would investigate the influence of source and detector geometries on the quality of imaging and characterization results. Particularly with the help of Dr. Leo Ongkiehong (a former colleague of professor Berkhout in Shell), the so-called DOLPHIN-consortium was founded in 1995. The objective was to introduce a new approach to the analysis of acquisition geometries by making use of the CFP-concept. An important tool in DOLPHIN was the downscaled acquisition system ('model tank') that was built with the group's knowledge on medical imaging instrumentation and the technical support of TNO. DOLPHIN started with 6 companies.

With the help of Dr. Gerrit Blacquière and Dr. Eric Verschuur (who both had successfully completed their Ph.D. thesis), DOLPHIN was fully integrated into the Delphi program.

Delphi today :

Acquisition and Preprocessing

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In A&P new concepts and algorithms are developed, the capabilities of which are demonstrated by examples

Delphi Consortium

Delphi today (A&P)

As we already mentioned in Chapter 2, the Delphi research program is now being organized according to the Seismic Value Chain. It consists of three interrelated projects, each project containing a number of interrelated topics (**see Figure 3-2**).

Acquisition and Preprocessing (A&P) project

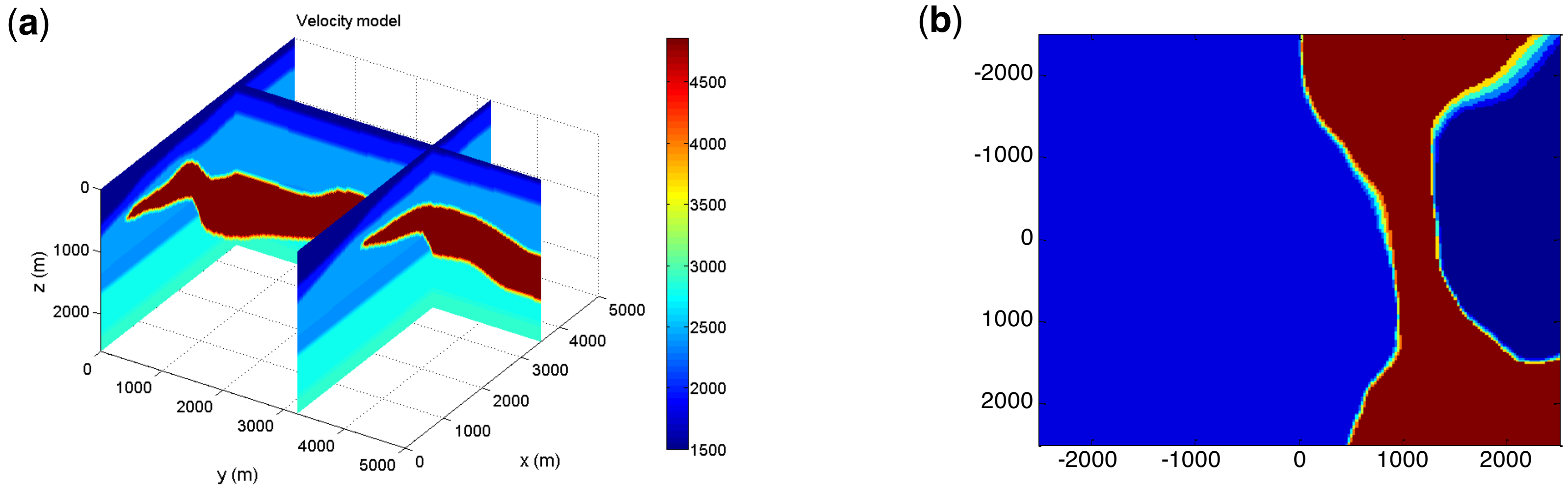
The Delphi Acquisition and Preprocessing project (node 1) aims at improved data acquisition geometries as well as new preprocessing concepts for land and marine seismic data.

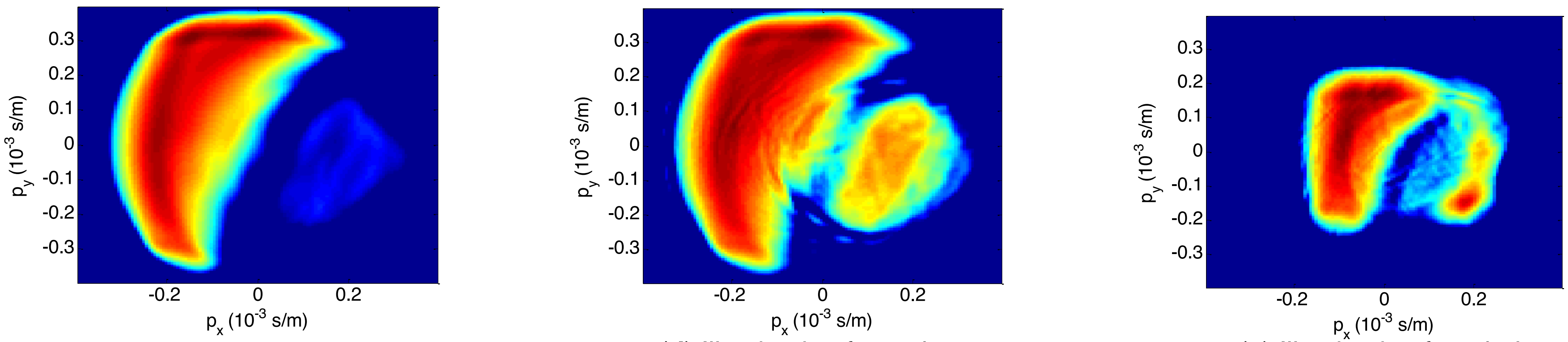
The acquisition and preprocessing project (A&P) contains the following interrelated research topics:

- interactive design for optimum acquisition geometries , including the effect of blending and the extra illumination properties of the multiples (**Figure 5-1**);
- the new concept of dispersed source arrays (**DSA's, Figure 5-2**);
- advanced source coding techniques (**Figure 5-3**)
- deblending technology for separating overlapping shot records (**Figure 5-4**);
- source and receiver deghosting, by considering it as a deblending problem (**Figure 5-5**);
- solving the complex near surface problem via full wavefield imaging and velocity estimation technology (**Figure 5-6**).

Next page to see figures

Delphi today (A&P)





(**c**) Illumination from above
Primaries-only

(**d**) Illumination from above
Primaries as well as multiples

(**e**) Illumination from below
multiples-only

Figure 5-1: Example of including multiples for illumination in the 3D Ziggy salt model (**a**) using a full source geometry for one target location (**b**). Due to the complex overburden, the primaries can only provide a limited illumination angles at a target reflection point below the salt (**c**). However, when including multiples significantly increases the illumination properties below the salt (**d**). In addition, the internal multiples that reach the target point from below (**e**) will provide even more illumination angles.

Delphi today (A&P)

Figure 5.2

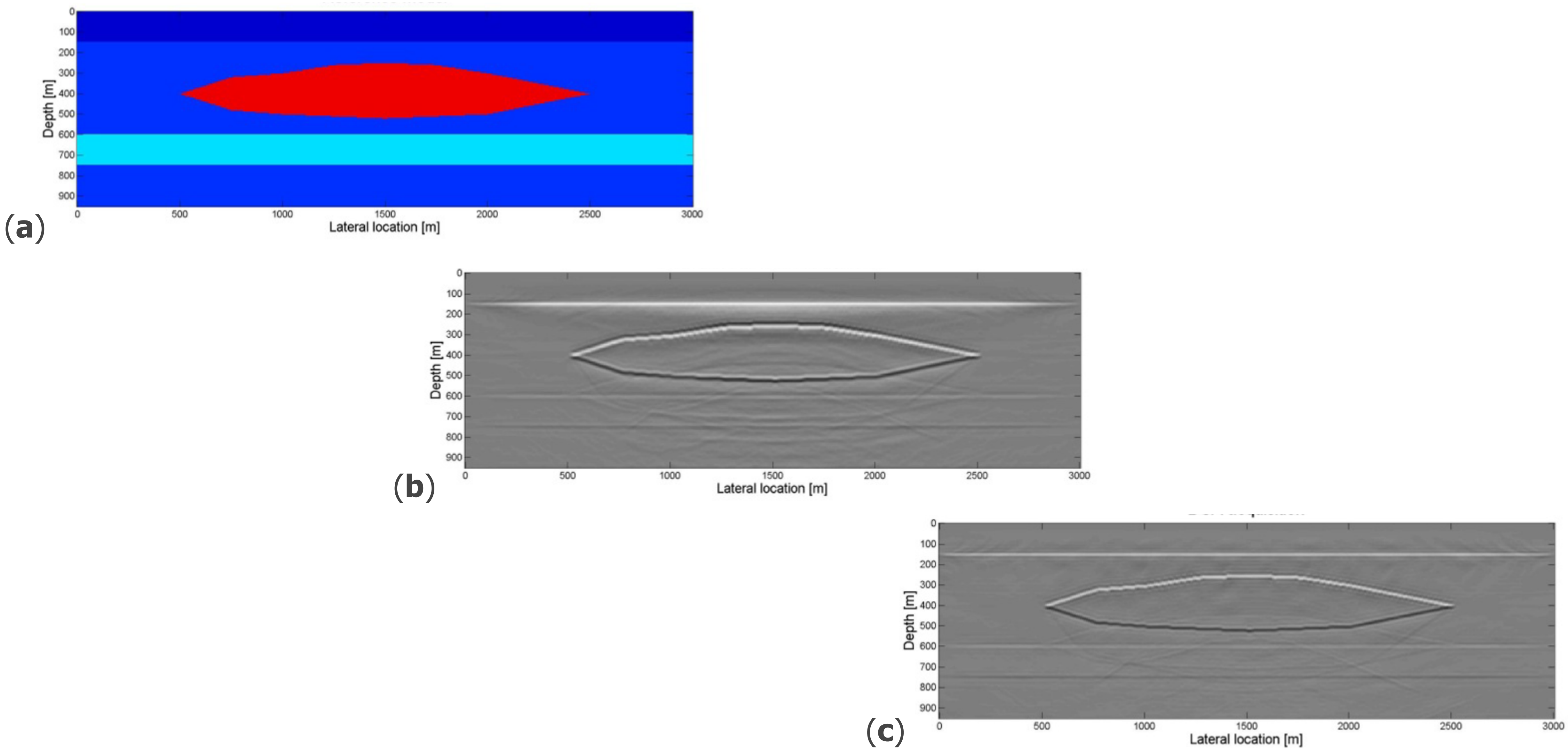
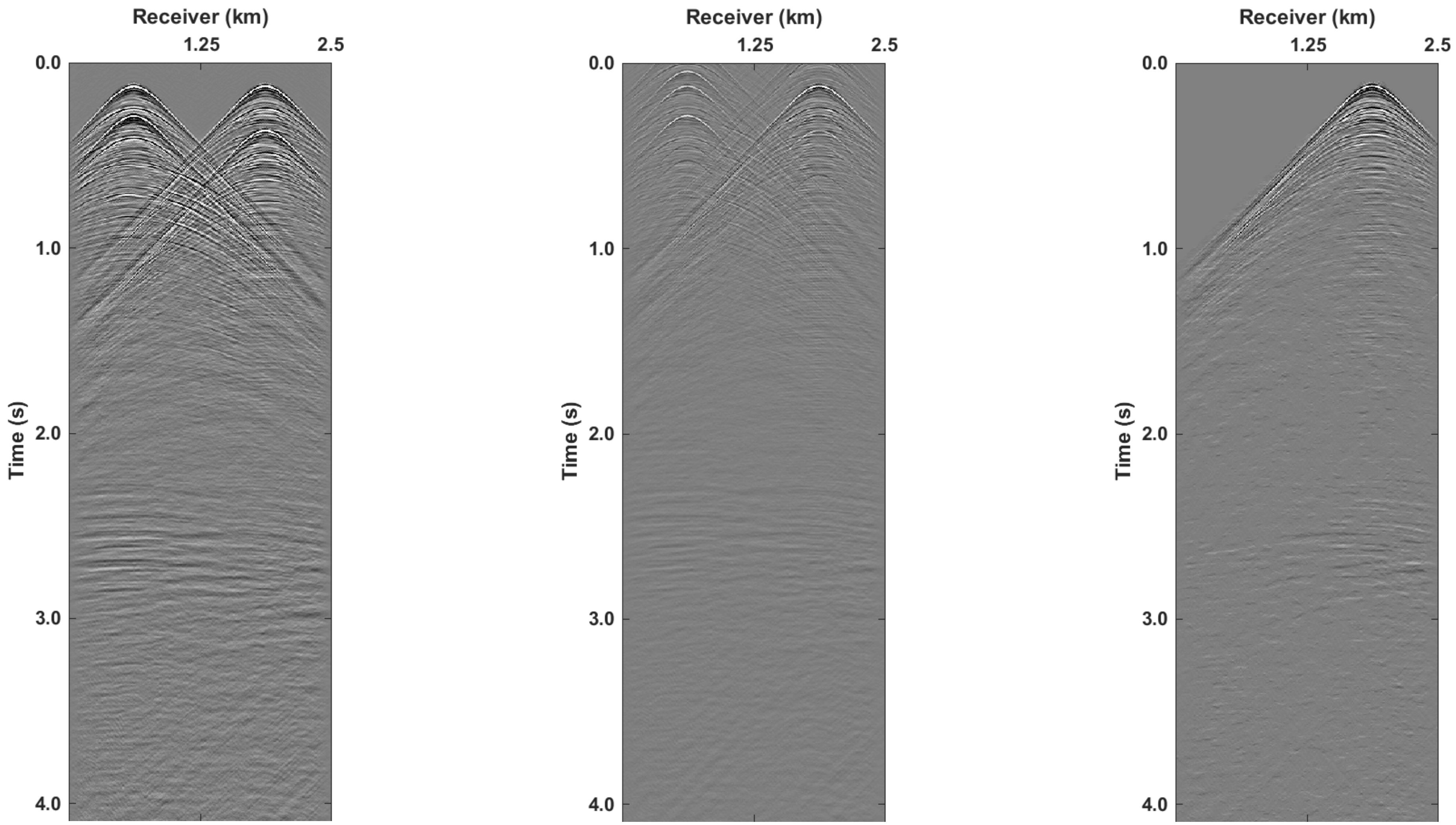


Figure 5-2: A new concept in blended acquisition is to use different sources with different frequency bands at different spatial sampling distances: dispersed source arrays (DSA's). With the Delphi-developed Full Wavefield Migration process (see M&I project) these measurements can be easily combined to one high-resolution image. (**a**) Subsurface model for generating test data. (**b**) Image with conventional acquisition. (**c**) Full wavefield image using DSA data.

Delphi today (A&P)



(**a**) Blended with shot repetition (**b**) Pseudo-deblending (**c**) Iterative deblending

Figure 5-3: Deblending capabilities can be improved when using specially designed shot repetition patterns, in stead of just simple time delays, in blended acquisition. Using blending with this source coding (**a**), the pseudo-deblending process already provides a good initial separation (**b**). Deblending here is demonstrated by iterative blending-deblending with amplitude thresholding (**c**). Note that this experiment shows numerically blended field data.

Delphi today (A&P)

Traditionally, seismic acquisition surveys are designed such that the time intervals between consecutive shots is sufficiently large to avoid the tail of the previous source response interfering with the next one (zero overlap in time). To economize on survey time and processing effort, the current compromise is to keep the number of shots to some acceptable minimum. The result is that in current practice the source domain is poorly sampled.

In Delphi it is proposed to abandon the condition of non-overlapping shot records. Instead, a plea is made to move to densely sampled and wide-azimuth source distributions with relatively small time intervals between consecutive shots (**‘blended acquisition’**).
The underlying rationale is that interpolating missing shot records, meaning generating data that have not been recorded, is much harder than separating the data of overlapping shot records (**see Figure 5-3, 5-4**). In other words, removing interference (**Figure 5-3**) is preferred over removing aliasing. Furthermore, with the concept of dispersed source arrays, where sources with different frequency content are used in a blended experiment (**see Figure 5-2**), the acquisition design can be further optimized to minimize cross-talk. In addition, the concept of simple time delays in blended acquisition can be augmented by the use of source repetition patterns (**see Figure 5-3**) in order to facilitate deblending algorithms (**Figure 5-4**). Furthermore, the ghost problem can be considered as a blending problem and resolved with similar approaches (**see Figure 5-5**).

Delphi today (A&P)

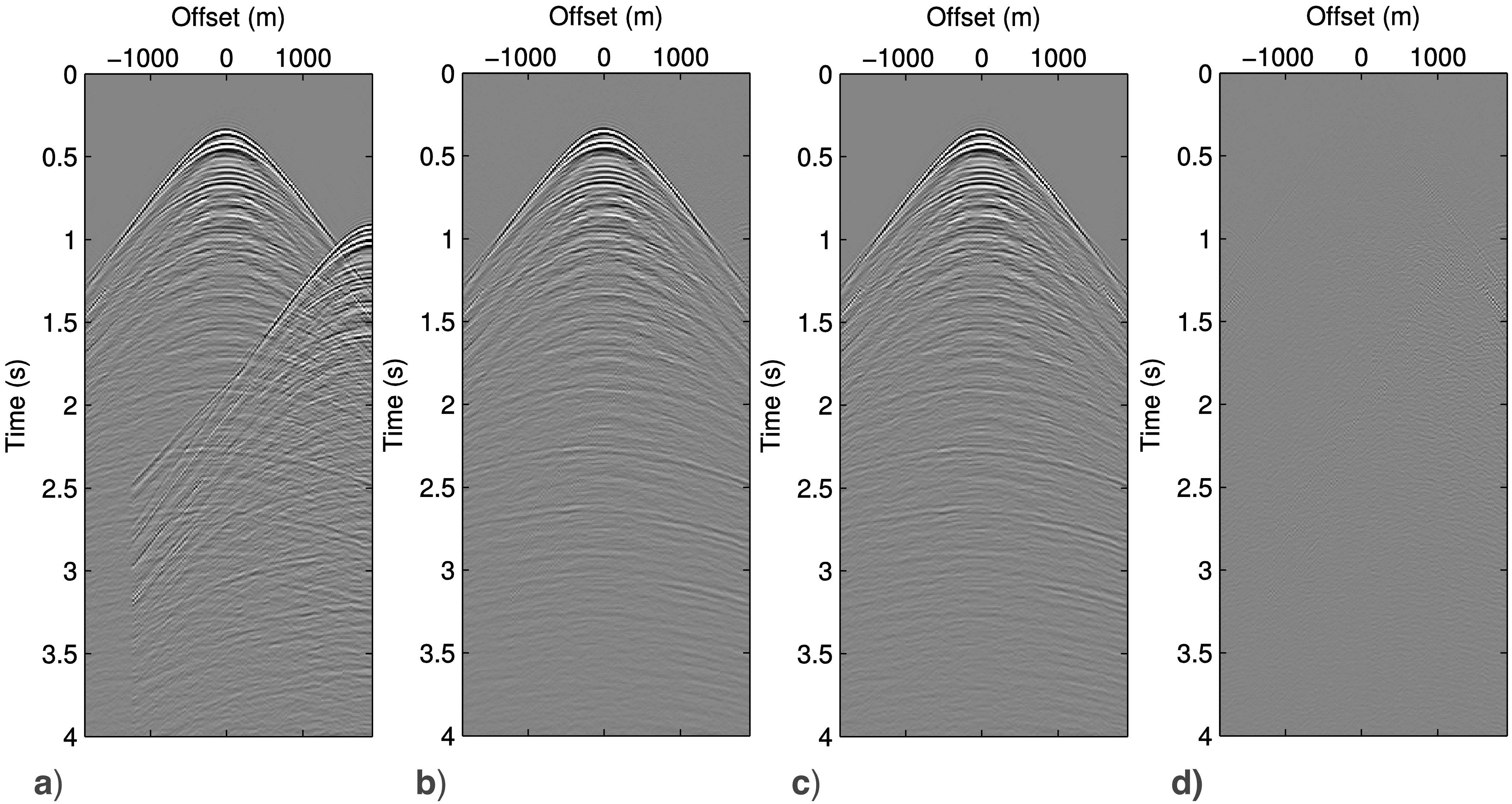
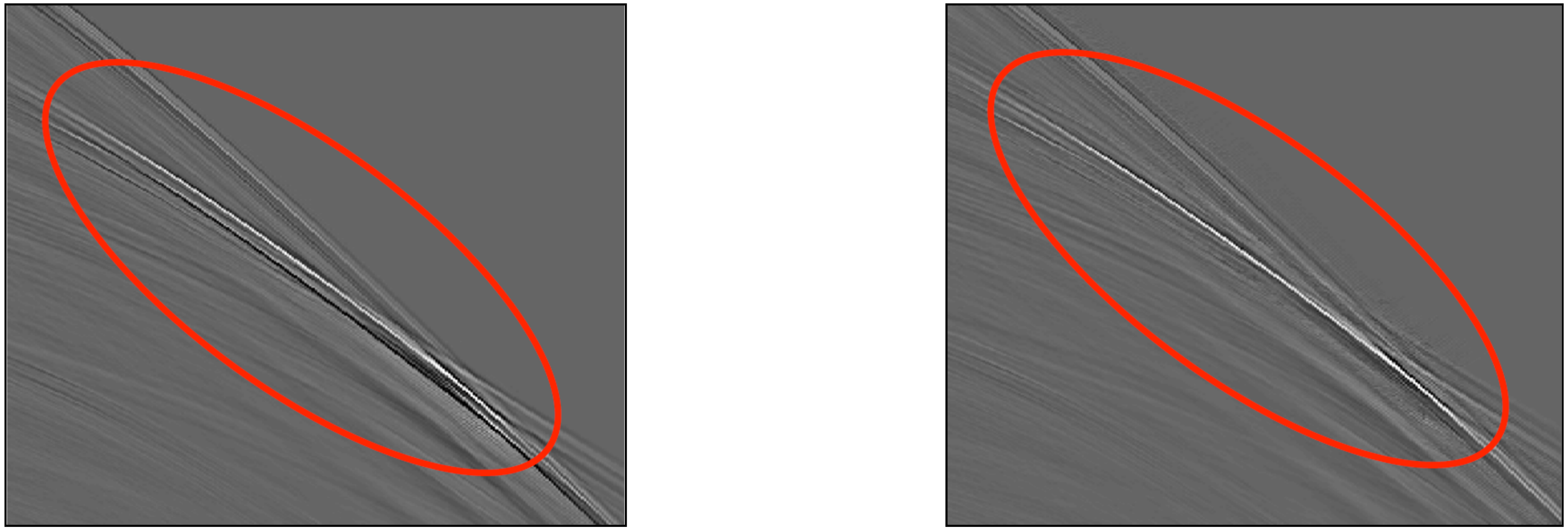


Figure 5-4: Result of the deblending algorithm via sparse inversion with a focal transform constraint, for a simulated marine blending experiment. **a**) Pseudo-deblended shot record; the noise of a second shot is clearly visible. **b**) Deblending result. **c**) Original, unblended data. **d**) Difference between **b**) and **c**), i.e. the deblending residual.

Delphi today (A&P)



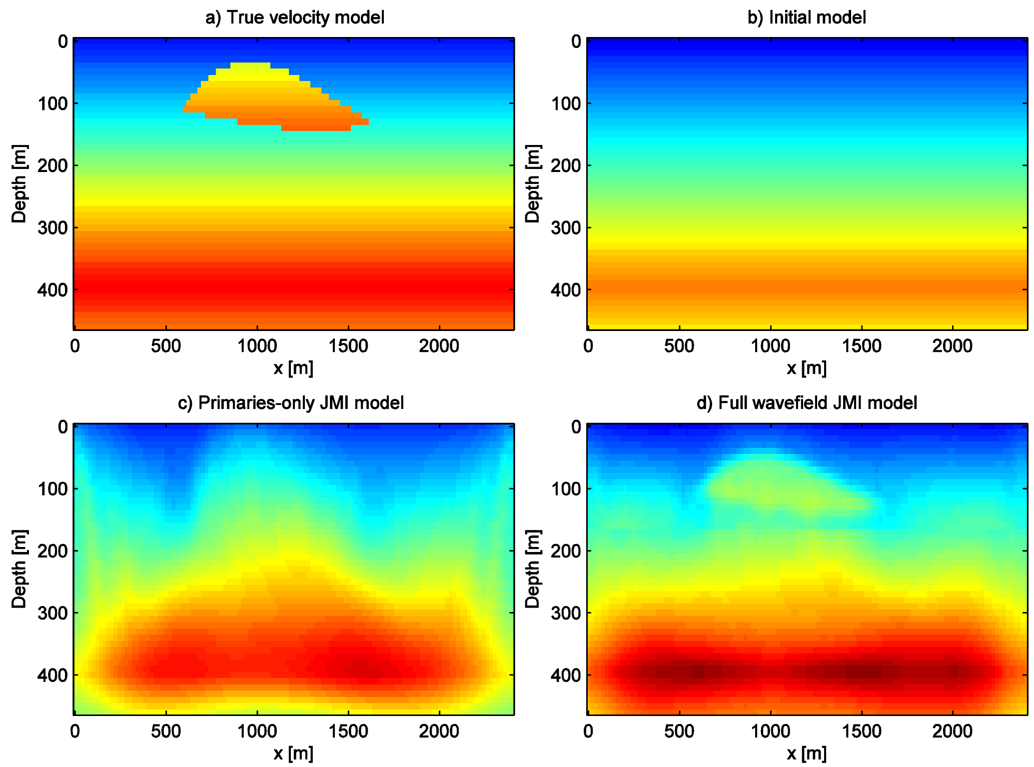
a) b)

Figure 5-5: Result of the wavefield extrapolation-driven deghosting procedure on field data.
a) Shot record with ghost from deep tow, **b**) Shot record after deghosting.

Delphi today (A&P)

In Delphi, the solution of the near surface is based on using all possible information from the near-surface area: the velocities can be resolved via the propagation imprint onto the deeper reflections and the reflection properties are encoded in the internal multiples that bounce downward in the near-surface layer and create a coda attached to each reflection event. Our Joint-Migration-Inversion (**JMI**) technology (**see the M&I project**) has the capabilities to utilize both characteristics (**see Figure 5-6**).

a) true velocity model **b**) initial velocity model



c) est. Model from deep primary **only** **d)** est. model using internal multiples

Figure 5-6: Numerical example of using internal multiples to resolve near-surface issues. **a**) Subsurface model with near-surface anomaly. **b**) Initial velocity model for the Joint Migration-Inversion (**JMI**) process. **c**) Estimated velocity model using primaries only. **d**) Estimated velocity model using primaries and internal multiples. Note the recovered near-surface anomaly and increased resolution in **d**).

Delphi today :

Multiple Estimation and Structural Imaging

6

In M&I new concepts and algorithms are developed, the capabilities of which are demonstrated by exam-ples

Delphi Consortium

Delphi today (M&I)

The goal of the Delphi Multiple Estimation and Structural Imaging project (**node 2**) is the transformation of marine (**single-component**), as well as OBC and land (**multi-component**) seismic measurements into highly resolved structural images.

The multiple estimation and structural imaging project (**M&I**) contains the following interrelated research topics:

- surface-related and internal multiple estimation (**see Figure 6-1 and Figure 6-2**);
- using multiples to estimate missing (near) offsets (**see Figure 6-3**);
- imaging of blended seismic data, optionally including surface multiples (**see Figure 6-4**);
- imaging using also internal multiples, i.e. full wavefield migration (**see Figure 6-5**);
- estimation of the velocity model , i.e. joint migration-inversion (**see Figure 6-6**), also including anisotropy (**see Figure 6-7**)

The focus in the M&I project is not only separating primaries from multiples, but also using both primaries and multiples in the migration process (**FWM**). Hence, multiples are considered as important information. In addition, the migration process has been extended to simultaneously estimate velocity as well (**JMI**). We expect that multiple utilization and simultaneous velocity estimation will improve the quality of seismic images beyond expectation.

Next page to see figures

Delphi today (M&I)

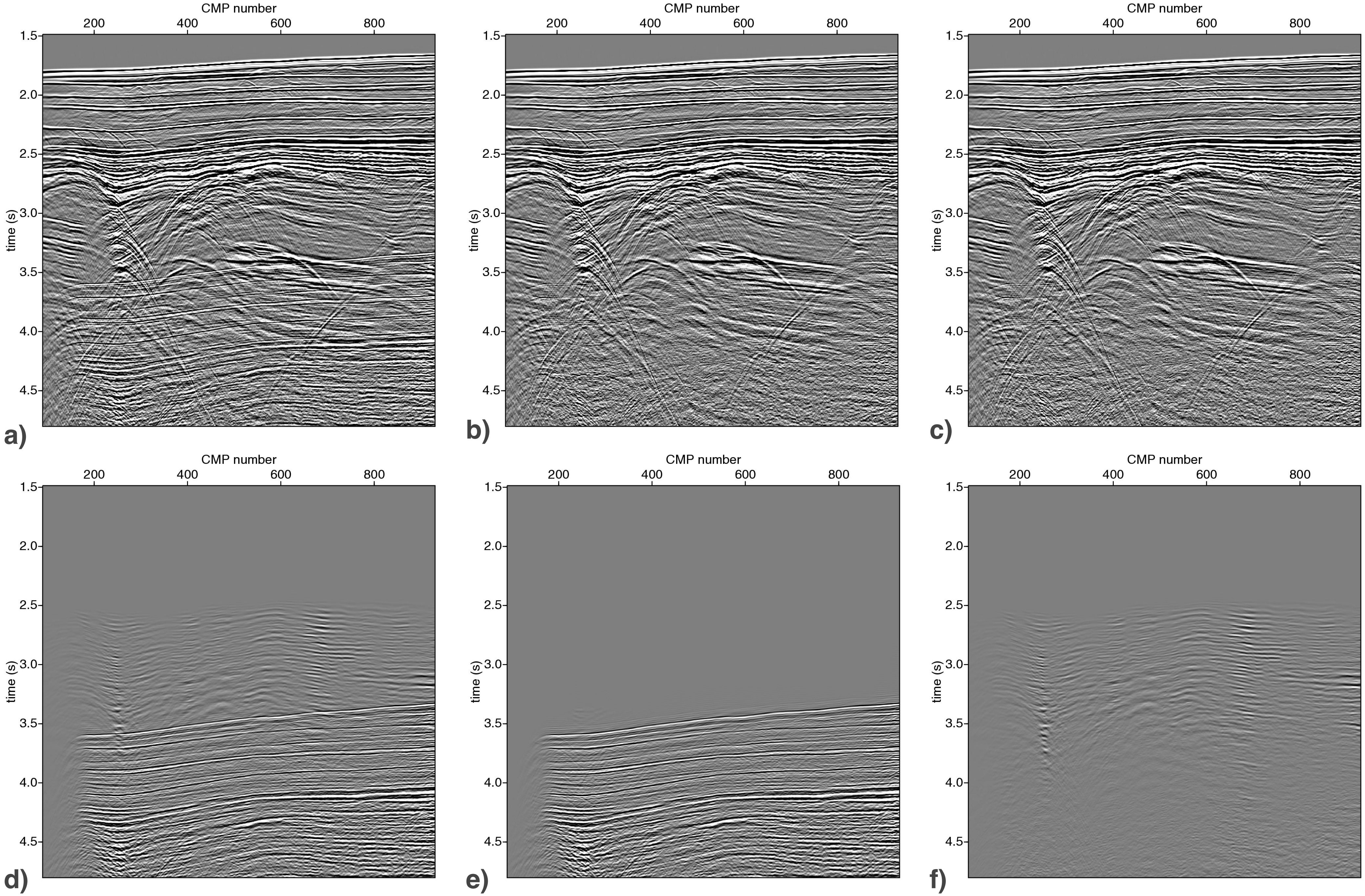
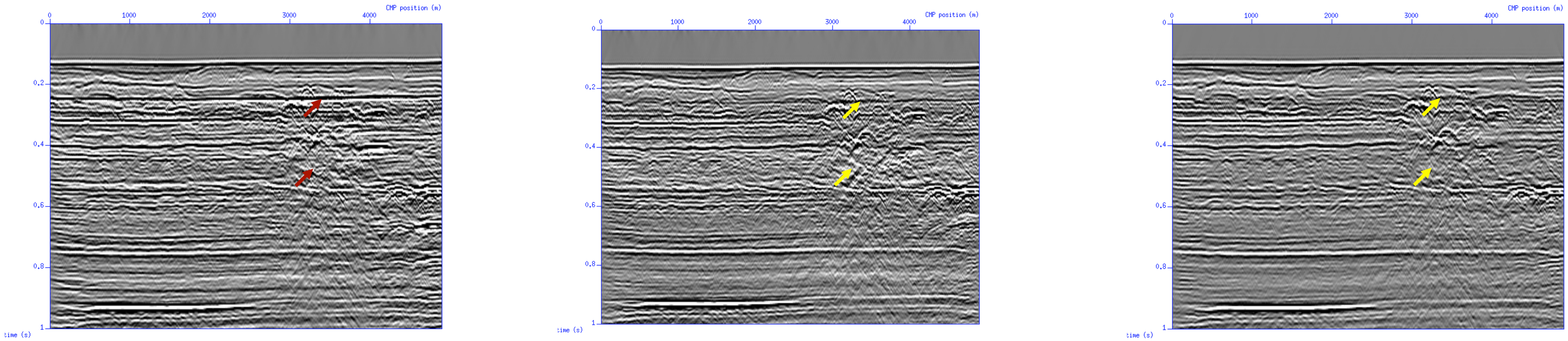


Figure 6-1: Example of pre-stack surface-related and internal multiple elimination for a North Sea dataset (**courtesy Statoil**). **a**) Stacked section with all multiples. **b**) Stack of all removed multiples. **c**) Stacked section after surface-related multiple removal. **d**) Stack of removed surface-related multiples. **e**) Stack after surface-related and internal multiple removal. **f**) Stack of removed internal multiples.

Delphi today (M&I)



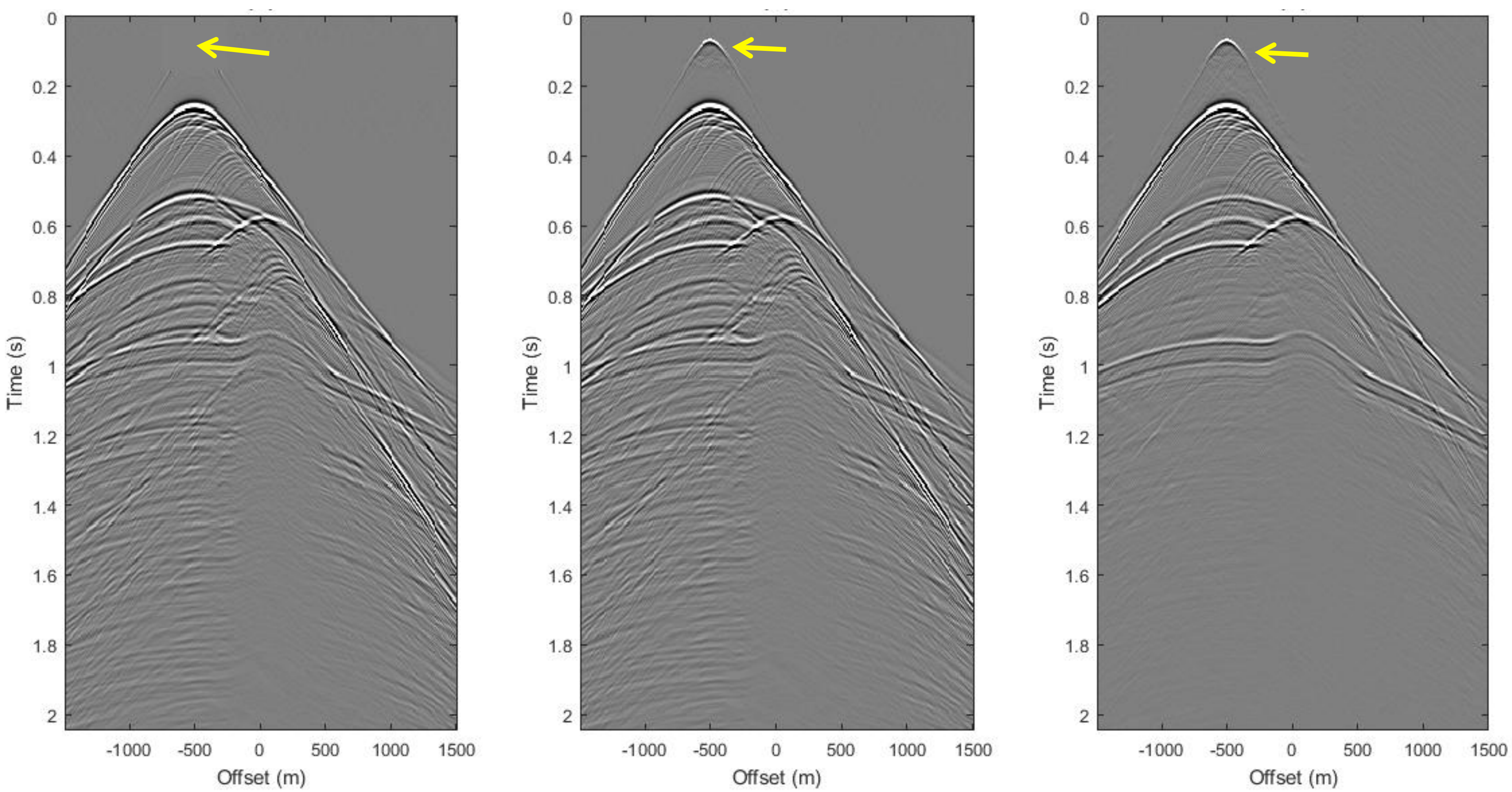
a) Stack with multiples

b) Stack after conventional SRME

c) Stack after EPSI (**closed-loop SRME**)

Figure 6-2: Example showing Estimation of Primaries by Sparse Inversion (**EPSI**) on field data, provided by PGS. **a**) Input stack with multiples. **b**) State-of-the-art SRME result. **c**) EPSI (**or closed-loop SRME**) result. Note the improved suppression of multiples by the EPSI method, as indicated by the arrows.

Delphi today (M&I)



a) input **b**) reconstructed data **c**) reconstructed primaries

Figure 6-3: Example of closed-loop SRME (**CL-SRME)** using the focal transform. **a**) Input shot record with near-offset gap indicated. **b**) Reconstructed data, where the first reflection event is almost fully reconstructed from the multiples. **c**) Estimated CL-SRME primaries. Note the almost perfect suppression of all surface multiples.

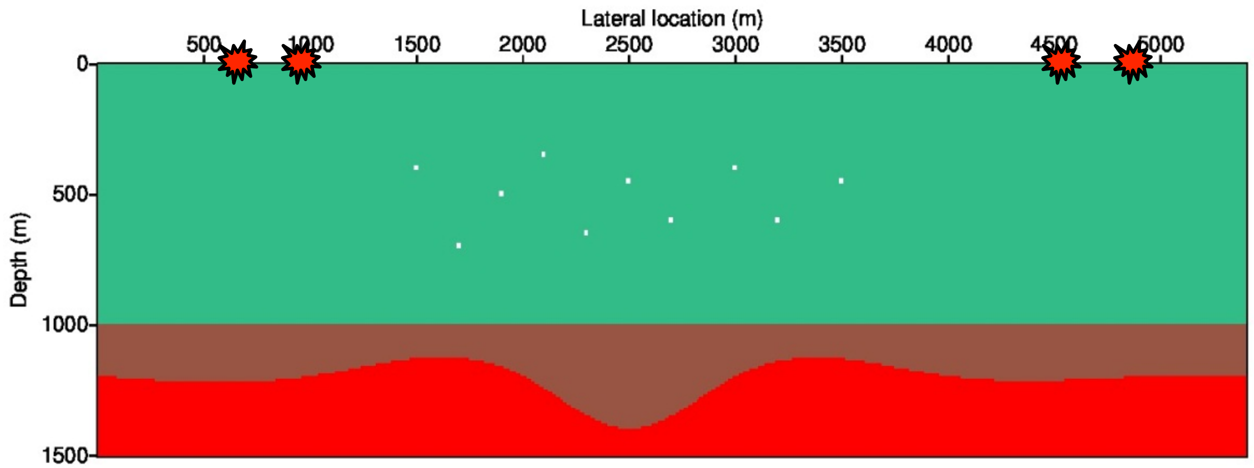
Delphi today (M&I)

Recently, the traditional SRME process is being reformulated as a large-scale inversion process, which we call Closed-Loop SRME. The aim is to directly estimate primary reflections from the measured data, such that these primaries - together with the associated multiples - explain the measured data. It turns out that multiples can be used to reconstruct the data and the primaries at the missing (near) offsets. This makes Closed-loop SRME especially suited for the situation of shallow water (**see Figure 6-2**). Currently, a 3D extension of closed-loop SRME is developed, which makes use of the focal transform for handling the aliasing problem. For a 2D case, Figure 6-3 already shows the added value of the closed-loop SRME algorithm with the aid of the focal transform: a complete missing shallow primary can be reconstructed using information from the multiples.

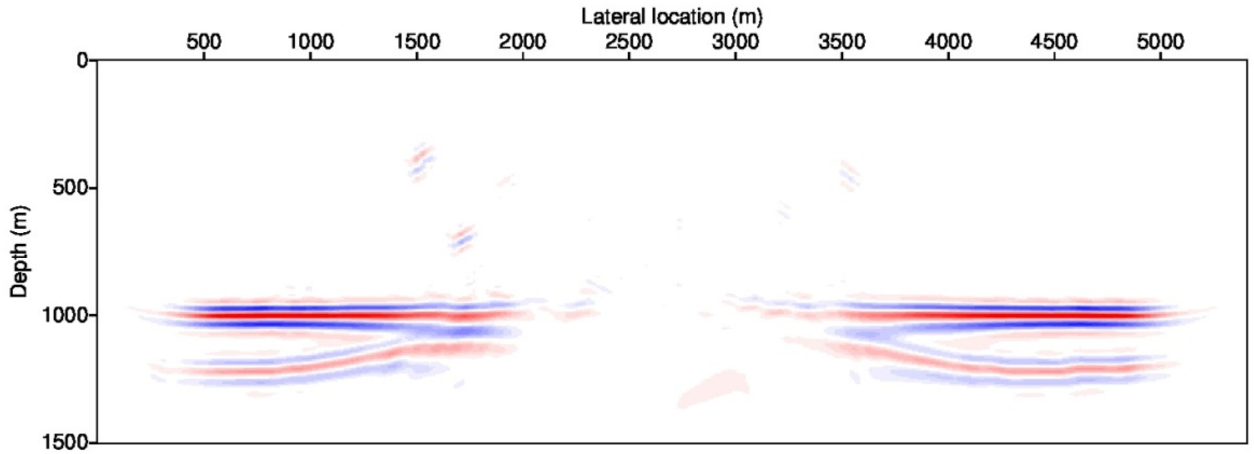
Furthermore, multiples can also contribute in the imaging process. Each order of surface-related multiples will provide an additional illumination of the subsurface, where each multiple will propagate under different angles. By taking this complex illuminating wavefield into account in the imaging process, a more densely sampled image can be obtained. With a similar reasoning, blended seismic data can be viewed as a complex illuminating source pattern, which can be properly accounted for in the migration algorithm (**see Figure 6-4**). We argue that deblending is not required: blended seismic data can be directly used in advanced imaging and inversion processes.

Delphi today (M&I)

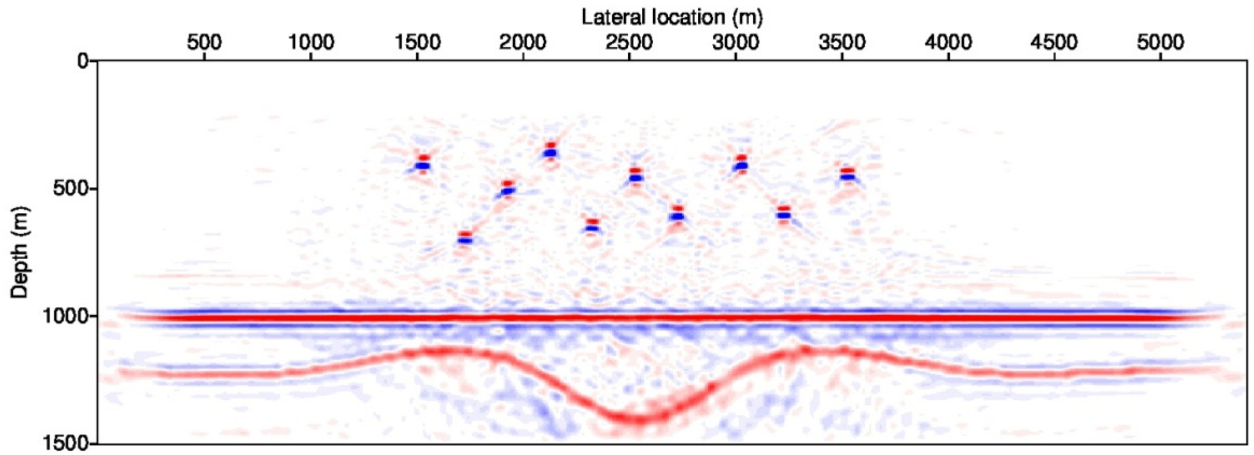
Figure 6-4: Example of using surface multiples in imaging **a**) Subsurface model showing the locations of the four shot records that have been used. Receivers are positioned along the complete surface. **b**) Image of the four shot records with primaries-only. **c**) Image using the full wavefield migration process, including all surface multiples. Note the extension of illumination and improvement of resolution when multiples are included, especially in the area where no source locations were present.



a) *subsurface model, showing the four source locations*



b) *pre-stack depth migration of primary data for four shots*



c) *full wavefield migration of four shots, including surface multiples*

Delphi today (M&I)

Currently, we are developing a migration scheme that also includes the internal multiples as part of the illuminating wavefield. In this full wavefield migration (FWM) process, at each depth level the inhomogeneities (represented by angle-dependent reflectivity) are illuminated from two sides: from above (by the downgoing source wavefields and multiples) and from below (by the upgoing primaries and multiples). In this manner, shadow zones in complex media can be resolved (see **Figure 6-5**).

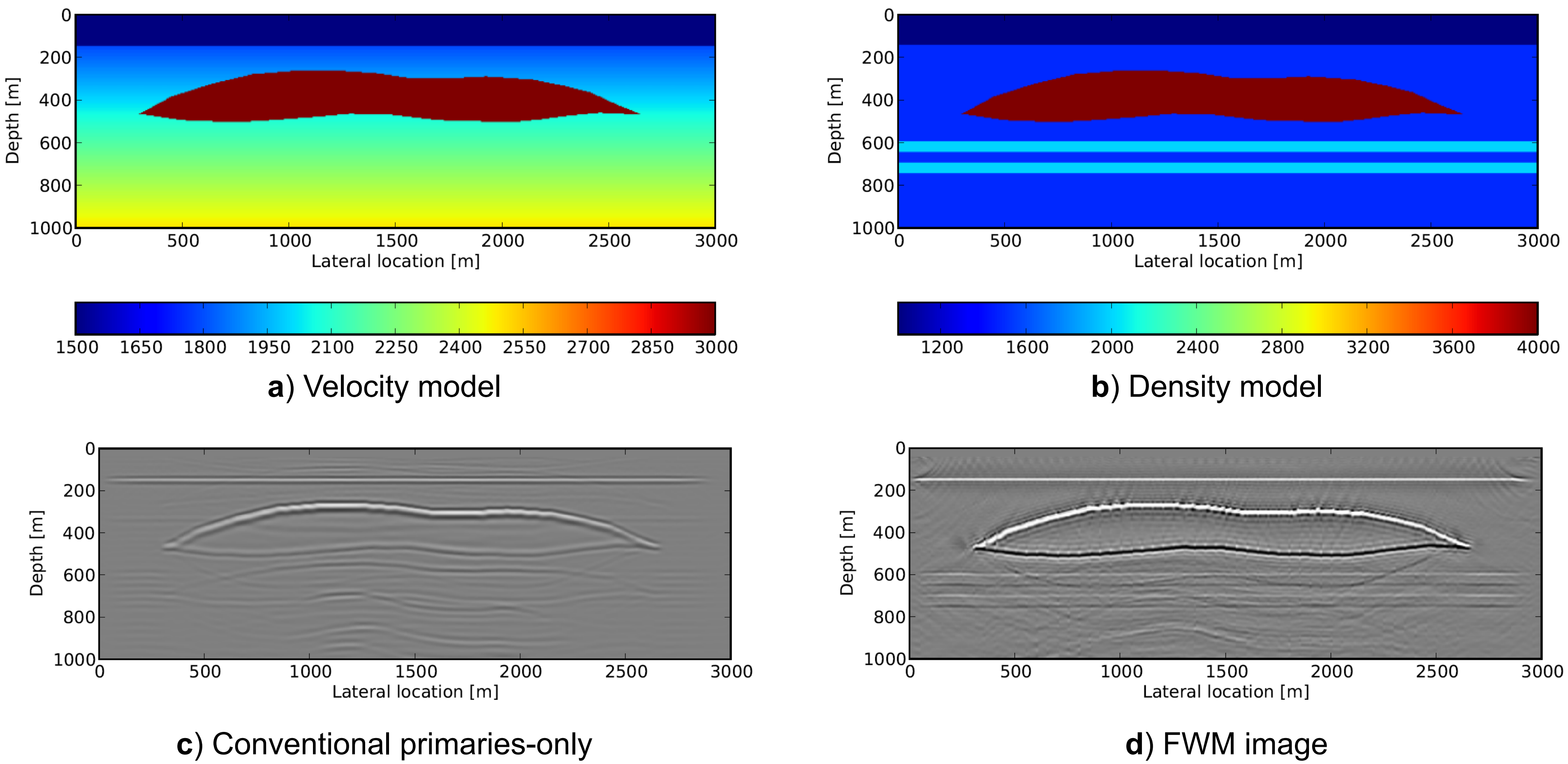
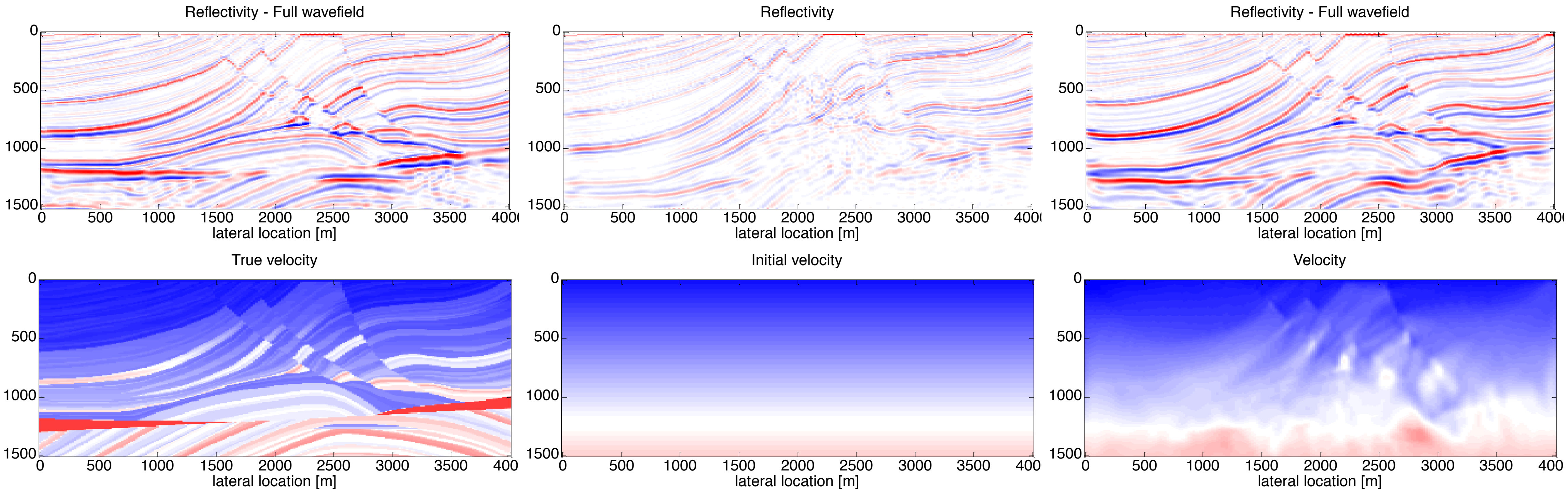


Figure 6-5: Example of Full Wavefield Migration (**FWM**), using internal multiples for high-resolution imaging. **a**) Subsurface model with high-velocity anomaly. **b**) Density model, showing the 'reservoir' layers. **c**) Depth image using primary illumination only (first iteration of FWM process). Note that multiples are imaged as cross-talk. **d**) FWM image, meaning that all multiples are included. Note the improved image in the deep part, also due to the proper handling of transmission effects. Crosstalk is suppressed and the weak reservoir reflections are now recovered.

Delphi today (M&I)

An extension of the full wavefield migration (**FWM**) process is the Joint-Migration-Inversion (**JMI**) process. Here, besides the estimation of reflectivity in each subsurface point also the propagation velocity is inverted for. Thus, the seismic reflection data are explained in terms of reflectivity and velocity, as demonstrated in Figure 6-6. Note that the JMI process is fully hands-off. Currently, we have extended the propagation effects to be angle-dependent (i.e. including anisotropy, see **Figure 6-7**). Also PS conversion can be included in this scheme.



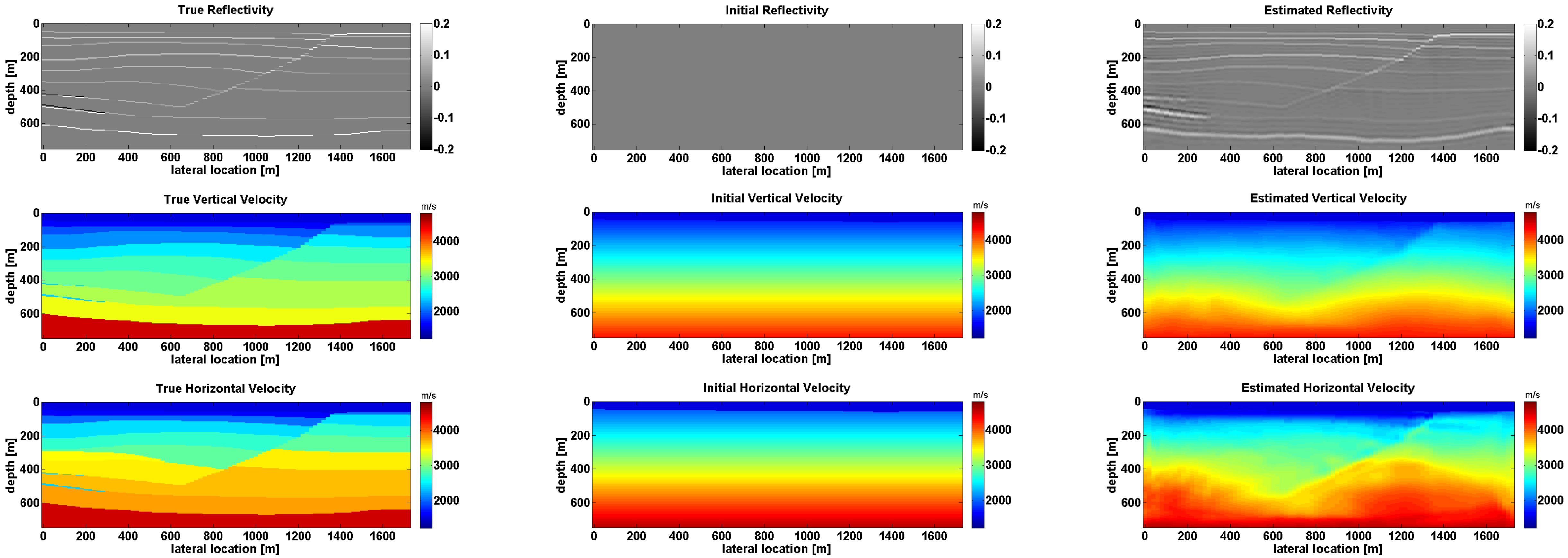
a) Full wavefield migration result with true velocity model image

b) Full Wavefield Migration result with- background velocity model image

c) Joint Migration Inversion result, starting from the background velocity model in **b**)

Figure 6-6: Example of JMI on the Marmousi model. **a**) The Full Wavefield Migration result obtained when using the true velocity model. **b**) The Full Wavefield Migration result obtained when using the initial velocity model. Note that the reservoir part of the model is completely distorted. **c**) The JMI result, starting from the initial velocity model. Note that the velocity model is reconstructed with an accuracy that is sufficient to image all parts of the model.

Delphi today (M&I)



a) True reflectivity and anisotropic velocity model (vertical and horizontal)

b) Initial image and velocity models

c) Joint Migration-Inversion result

Figure 6-7: Numerical example of JMI for anisotropic velocities, currently parameterized with fixed delta, and vertical and horizontal velocities. **a**) The true reflectivity and velocity models based on the so-called ‘Hess model’. **b**) The initial reflectivity and velocity models. **c**) The JMI result, starting from the models in **b**). Note that both vertical and horizontal velocities could be estimated quite accurately with the JMI process.

Delphi today :

Reservoir Characterization and Monitoring

7

In C&M new concepts and algorithms are developed, the capabilities of which are demonstrated by examples

Delphi Consortium

Delphi today (C&M)

The Delphi Reservoir Characterization and Monitoring project (**project number 3**) aims at bridging the gap between seismic imaging and reservoir engineering. Time-lapse seismic plays a key role, as it brings the three Delphi projects together in one double-loop interaction cycle.

Joint Migration-Inversion (**JMI**) is an excellent way to estimate the full wavefields in the reservoir, being required for Full Waveform Inversion (**FWI-res**) to start the inversion process in the reservoir. The output of FWI-res equals the elastic layer properties (**see Figure 7-1**). This inversion process can be repeated at any desired moment in the reservoir life cycle.

Similar to the objective of using multiple scattering in our imaging research, the essence of non-linear inversion is to make use of multiple scattering in reservoir property estimation. Using the JMI velocity model as a background medium (**output of project 2**), it involves full waveform inversion of the seismic data, not in terms of boundary parameters (as in migration), but in terms of elastic layer properties (**velocities and density**). In this way high-resolution estimates of the reservoir parameters are obtained at the scale of 5 meter. This process is called JMI-res, where the wavefields at each depth level resulting from the JMI process can be translated into the local elastic parameters. In a next step, these elastic parameters will be further translated to reservoir properties.

Figure 7-2 shows the huge potential of using all higher-order scattering effects in the data for a 2D numerical model based on the Delphi logo.

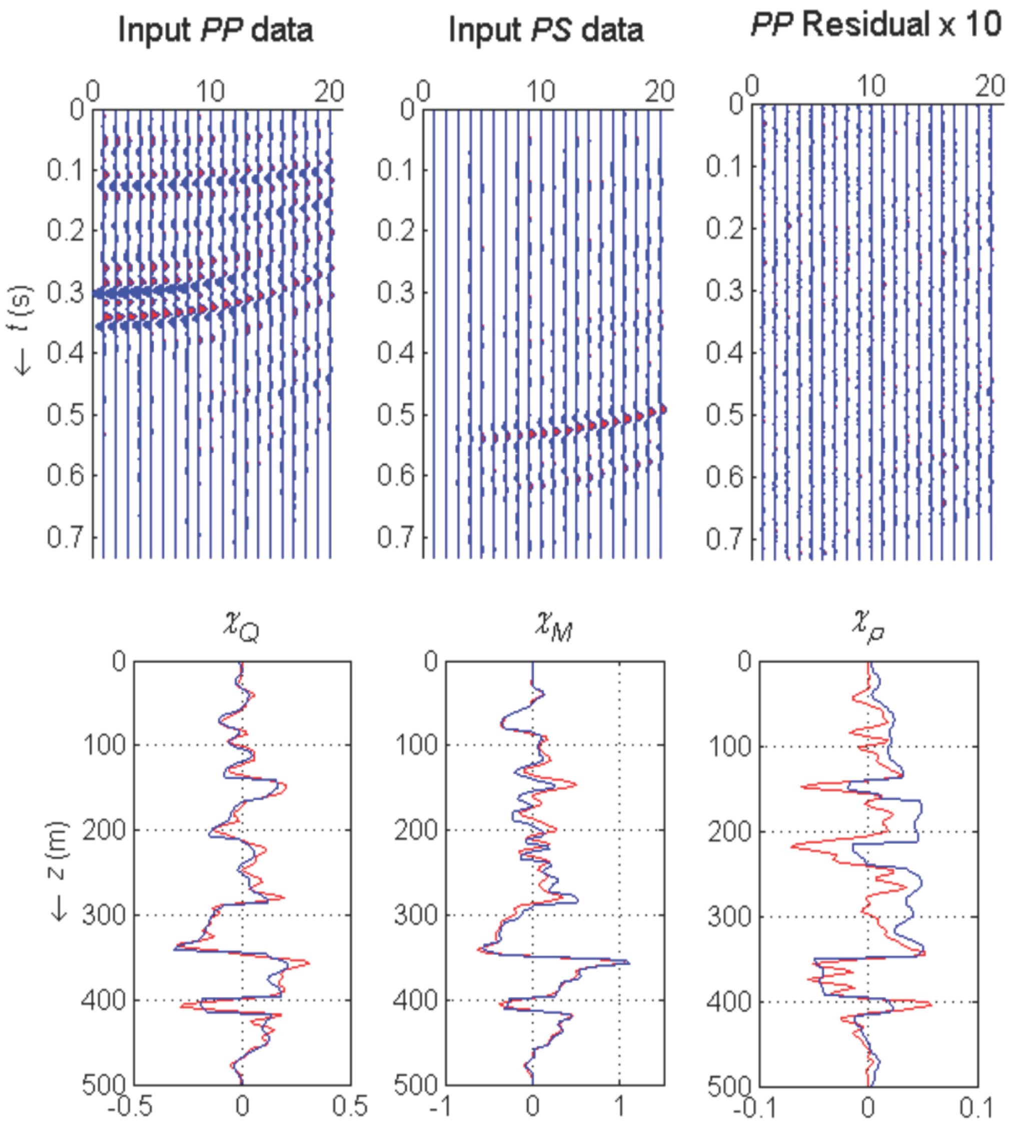
Next page to see figures

Delphi today (C&M)

Figure 7.1

a)

b)



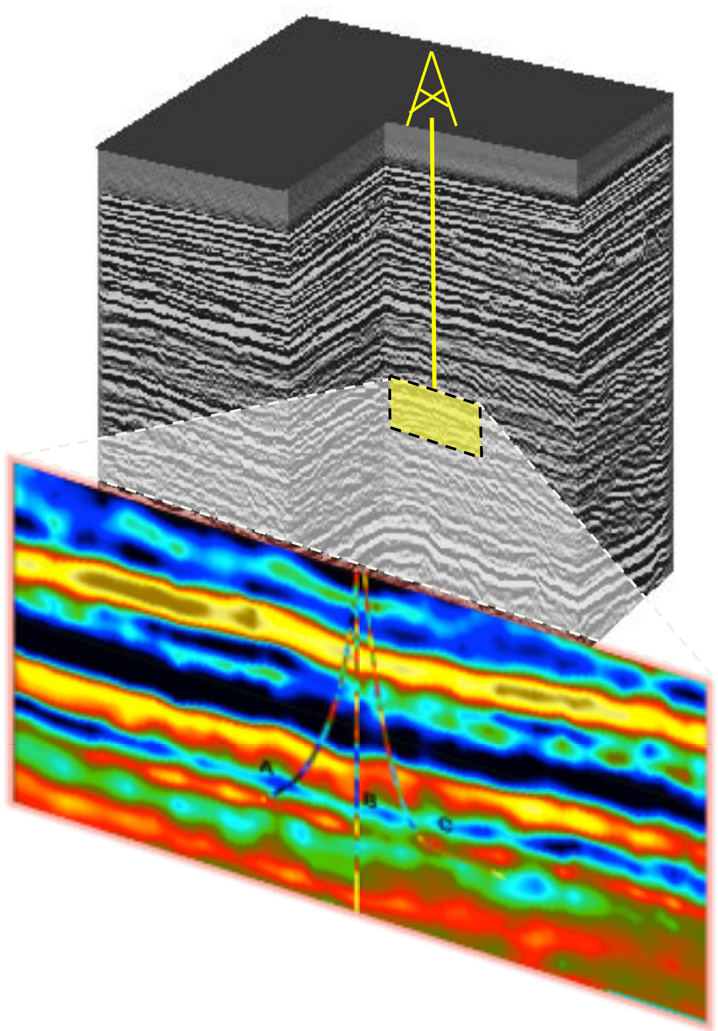


Figure 7-1 Example of full waveform inversion of a 1,5D medium at the reservoir level based on a true well-log. The wavefields at the top of the objective interval have been estimated by our Joint-Migration-Inversion (**JMI**) algorithm. **a**) Data in the τ-p domain and the residual after non-linear inversion, where the residual is blown up by a factor of 10. **b**) Estimated elastic parameters on a 5 m grid. Red shows the true values, blue the estimated values. The velocity-related parameters are very accurate, the density is only accurate in the mid and higher frequencies, as expected.

Delphi today (C&M)

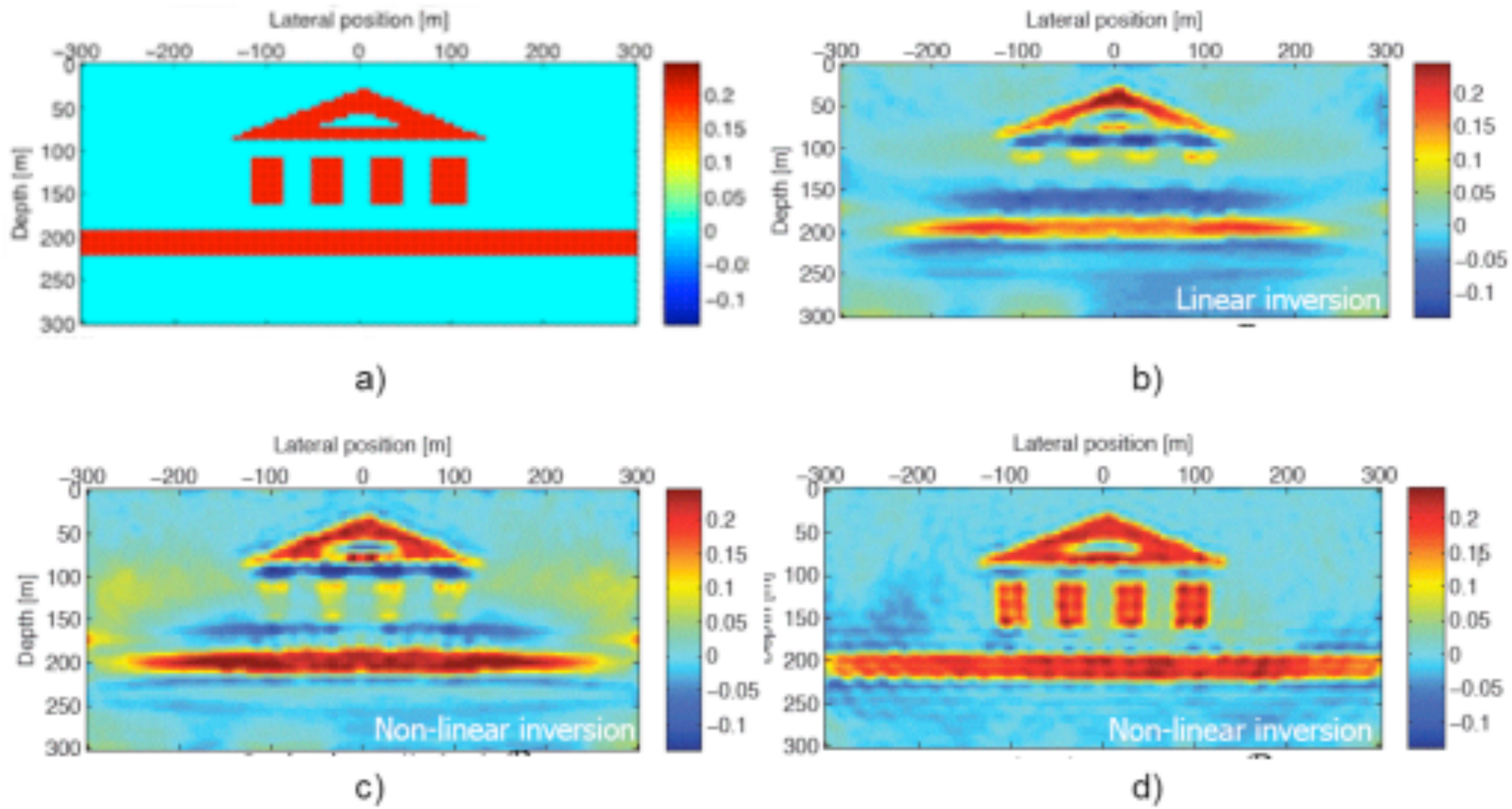


Figure 7-2: Example of 2D non-linear full waveform inversion. **a**) Single parameter subsurface model used to generate 2D seismic data. **b**) Result of linear inversion (first order scattering only). **c**) Non-linear inversion result using second order scattering. **d**) Non-linear inversion result using 50 orders of scattering. Note that the vertical reflectors are also properly reconstructed.

Delphi today (C&M)

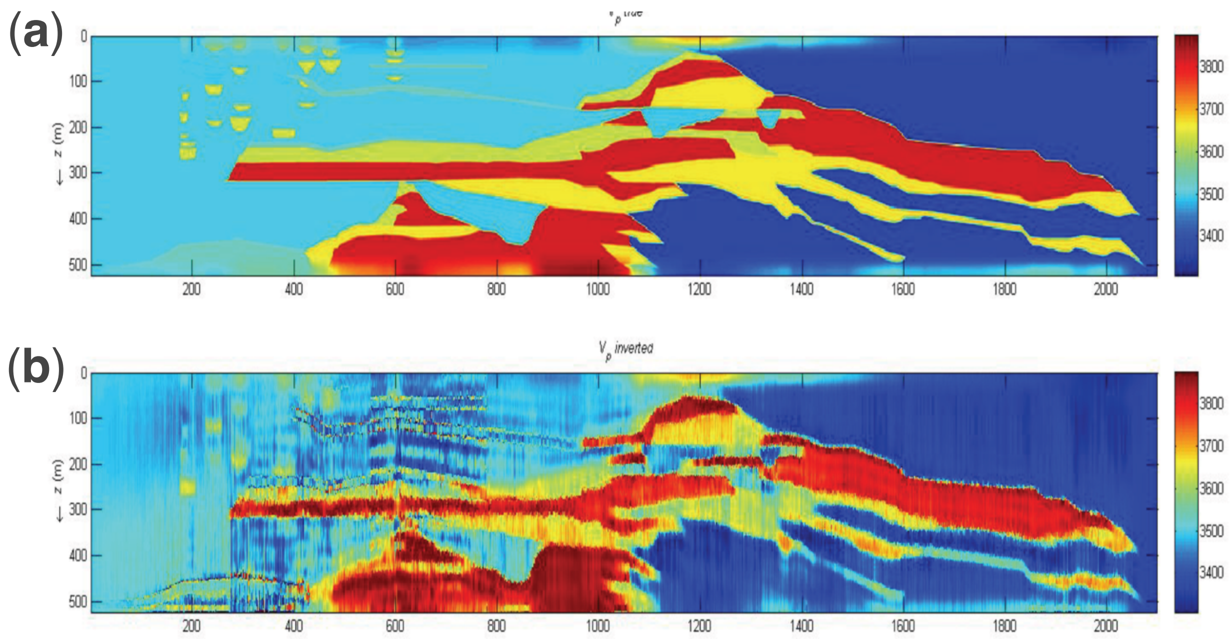


Figure 7-3: **a**) True *vP* profile based on an out-crop model. **b**) *vP* profile from three-parameter non-linear inversion. Inversion was performed on a 5 m grid. Note how well the channels have been resolved on the *vP* section. Overall this is an excellent inversion result, truly reconstructing all stratigraphic and sedimentological features put into the model.

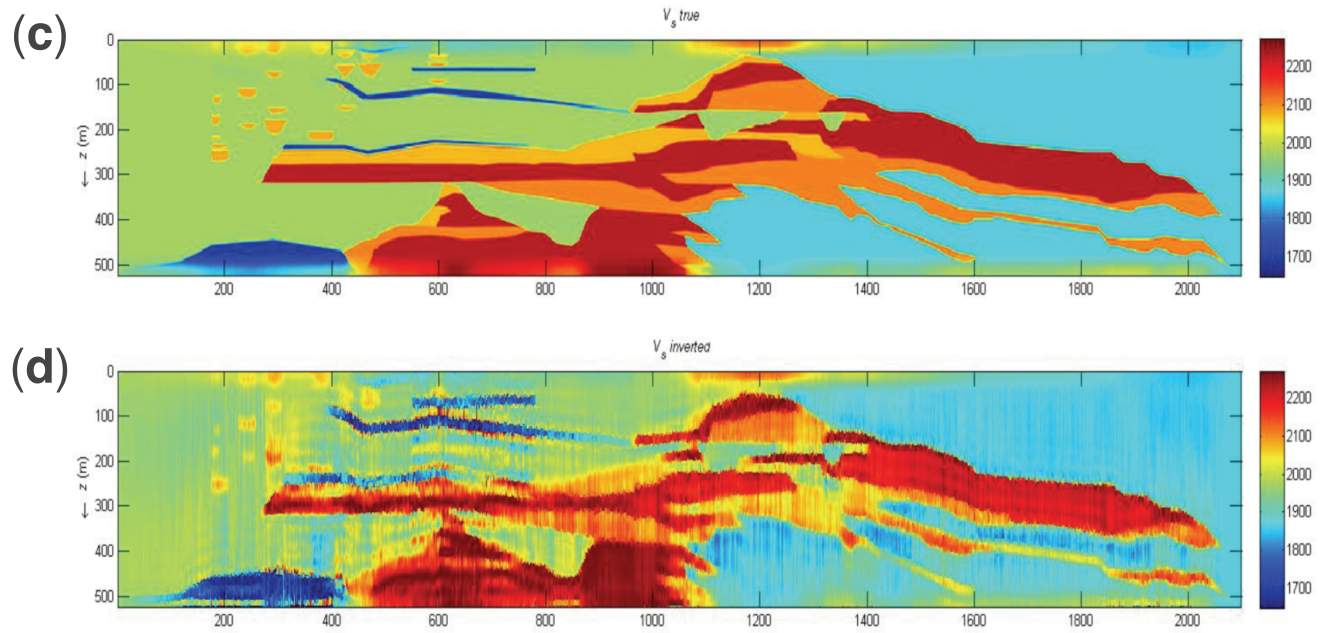


Figure 7-4: **a**) True *vS* profile constructed from the true outcrop model. **b**) *vS* profile from non-linear inversion. Note how well the coal seams have been resolved in this result.

Delphi today (C&M)

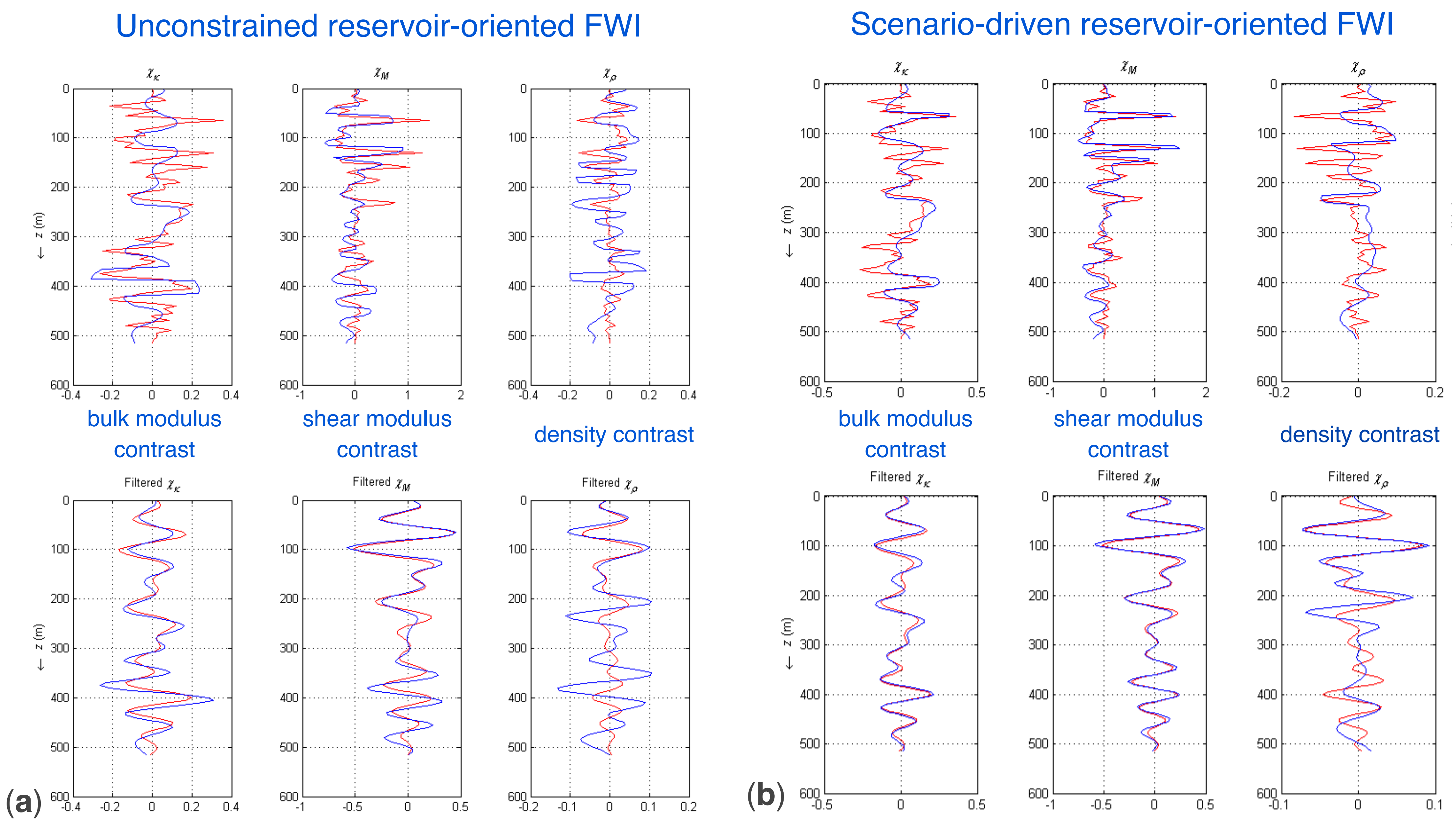


Figure 7-5 Scenario testing in reservoir-oriented full waveform inversion. (**a**) Estimated contrasts (**blue lines**) and the true contrasts (**red**) for the unconstrained inversion process. (**b**) Inversion results showing the estimated (**blue**) and true contrasts (**red**) using a suitable geologic scenario. Note that the final estimate is now more accurate.

Delphi today (C&M)

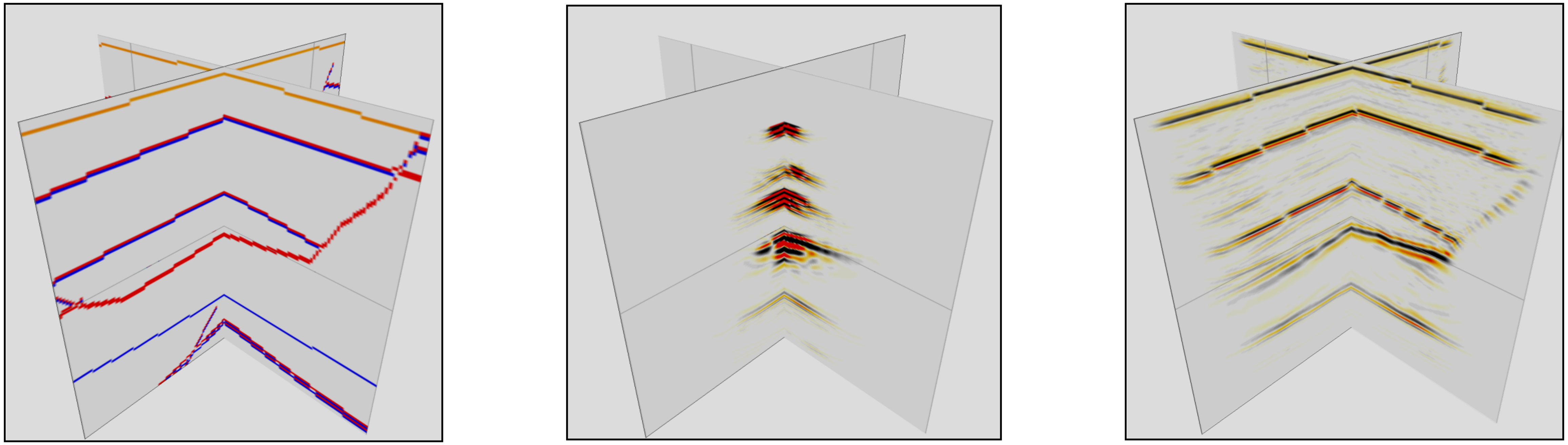
The three-parameter non-linear inversion results are shown in **Figure 7-3** and **Figure 7-4**, together with the actual properties. All lateral locations were inverted independently. A priori information taken into the inversion process consists of extremely smooth velocity and density fields, such as could have been obtained from seismic velocity analysis and gravity measurements. Note that even the smallest stratigraphic features in the model have been captured by our inversion, qualitatively as well as quantitatively. In addition, the robustness of the method can be verified by using different initial models and comparing the inversion results. In this way various geologic scenario's can be tested (**Figure 7-5**).

In addition to the non-linear inversion work, we focus on the processing and imaging of borehole data in order to get the maximum information on our reservoir. In **Figure 7-6** an example is given on using surface-related and internal multiples for accurate target-oriented 3D VSP imaging. Note the extension of the illumination area when multiples are included.

We aim at carrying out our Joint Migration-Inversion (**JMI**) process in a time-lapse mode (**Figure 7-7**). In this way we can localize small changes in the reservoir due to production and possibly changes in the overburden velocity distribution due to a change in the overburden pressure.

As a final step, the property changes obtained from time-lapse seismic are integrated into the reservoir history matching process. What we typically find here is that the property changes that can be detected by seismic occur along the moving saturation front and, consequently, provide improved estimates for the permeability parameters that are so important in reservoir simulation.

Delphi today (C&M)



a) True reflectivity

b) Conventional image

c) Full wavefield image

Figure 7-6: Full wavefield migration (**FWM**) of 3D walk-away borehole (**VSP**) data, using all multiple scattering. **a**) True subsurface model with avertical well located in the middle. **b**) Conventional image, using primaries only. **c**) FWM result, utilizing primaries and multiples. Note the improved lateral extension of the illumination and the increased vertical resolution.

Delphi today (C&M)

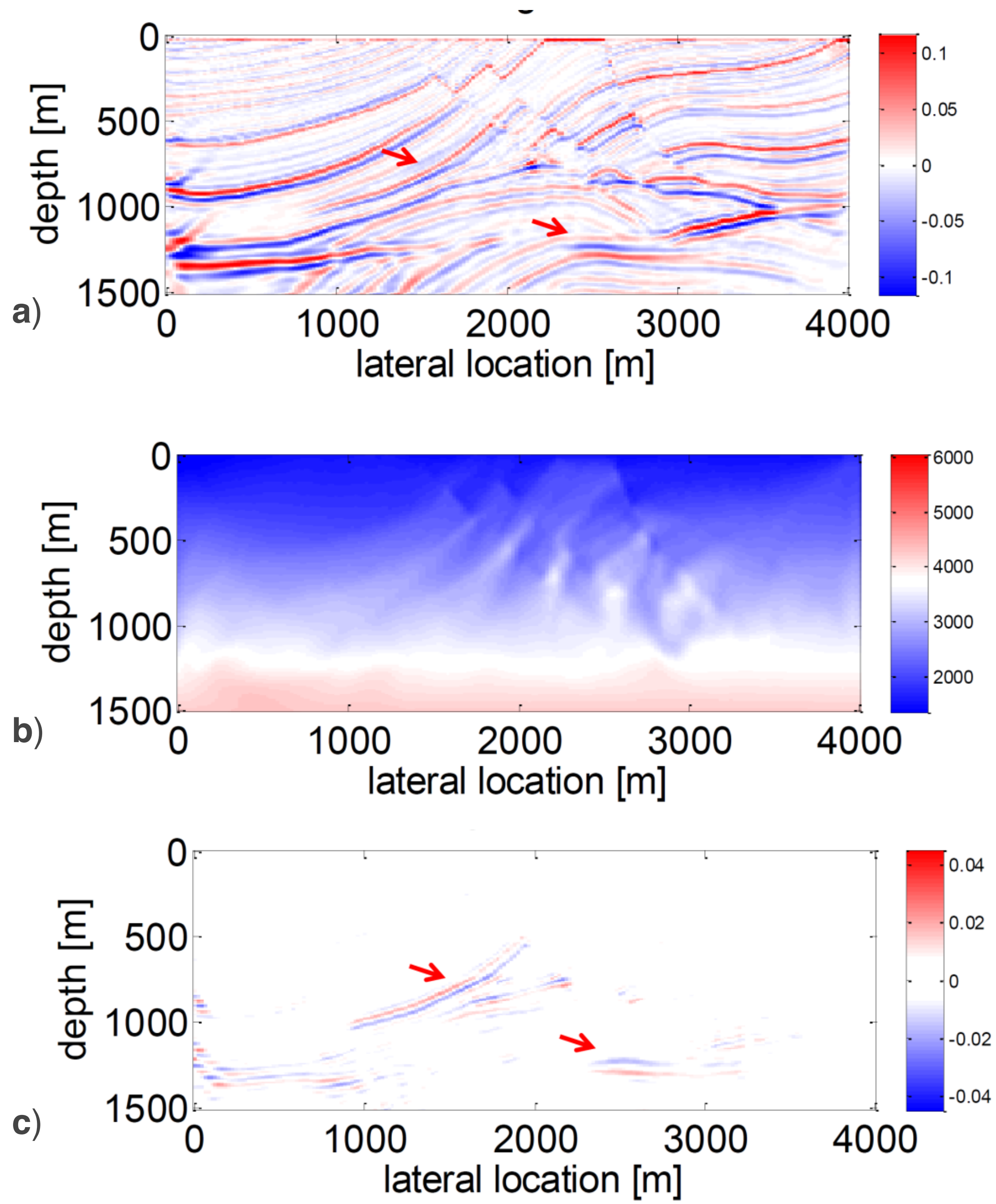


Figure 7-7: **a**) Example of time-lapse inversion with Joint Migration Inversion (**JMI**). Initial image of the Marmousi model (**see also Figure 6-6**), where the arrows point at two locations where a time lapse difference was included. **b**) Estimated velocity model after JMI. **c**) Image of the time lapse difference, meaning the difference of the JMI images from the base and monitor survey. Note that the time-lapse difference is well recovered.

The Delphi Research Team

8

The international members of the multi-disciplinary Delphi research team consists of senior and junior scientists

The DELPHI Research

Program and Project directors:

As of 1 January 2016 the foundar of Delphi, prof. Guus Berkhout, will resign from his duties and hand over the program directorship to Eric Verschuur. Together with Dr. Gerrit Blacquière they will lead the three Delphi projects (**A&P, M&I, C&M**) in the coming years.”

The Delphi team consists of scientists from the Applied Sciences faculty and the Earth Sciences department of the Delft University of Technology.

Team members:

- Advisors (by invitation)
- Guest scientists (by invitation)
- Post-docs
- Ph.D. students
- M.Sc. students
- Support team

Delphi deliverables

9

Consortium members receive reports, publications and software that includes demonstration examples

DELPHI deliverables

Delphi volumes: Once a year the Delphi sponsors receive a printed volume of the research results for each of the three Delphi projects. Electronic versions (PDF files) are available through the private web-pages.

Sponsor meetings: Twice a year a Delphi sponsor meeting is organized: one in Houston and one in The Hague. The first one is in the beginning of February and the second one in the beginning of June, just prior to the annual EAGE meeting.

Software releases: We have organized the technology transfer to the sponsors by providing operational software releases (no additional costs), installation services (variable costs) and dedicated in-house seminars (variable costs).

Within the Delphi consortium interactive software is developed, which is available to the sponsors as source code. The Delphi software releases consist of a package of programs and subroutines, written in Fortran and C (and some in Matlab), which are tested on the most frequently used computer systems. The software can be used in combination with the Seismic Unix software, which is available from Colorado School of Mines without cost.

By means of a protected website the latest version of the Delphi codes can be retrieved and compiled at the sponsors' site.

The software contains a large list of demo’s to check the working of the code. Most of these demo’s are available directly accessible online, without the need of installing any software.

Delphi Data services: We have organized sponsor-dedicated technology application at Delft by offering experimental data processing services. These services are provided by the Delphi Studio (see next section).

Employees of sponsoring companies can enroll at the Delft University (M.Sc., Ph.D.) as a member of the Delphi team.

Delphi Studio for Imaging (DS4I)

10

Delphi technology can be applied to the data of Delphi sponsors by making bilateral arrangements (‘experimental processing services’)

Delphi Studio for Imaging (DS4I)

The objective of Delphi is to develop new concepts in (robotized) seismic acquisition and preprocessing, full wavefield migration (FWM), joint migration-inversion (JMI) and full waveform inversion (JMI-res) to decrease the uncertainties in subsurface models. So far, algorithms have been developed on the topics of acquisition design for coherent and incoherent shooting, deblending, near-surface preprocessing, data-driven primary-multiple separation (closed-loop SRME), automatic velocity estimation combined with full wavefield migration (JMI) for surface and VSP data.

In Delphi, new concepts are tested on our synthetic and / or field data ('proof of principle'), but execution of processing jobs – how useful they may be for giving practical experience to our students – is not aimed for. In the consortium we prefer to keep the focus on developing and testing new concepts.

In the last few years, however, we obtain an increasing number of requests to apply Delphi algorithms to the data of our sponsors. This is particularly the case for complex situations in land and marine, where current technology does not give satisfactory answers. Actually, many of the new sponsors inquire whether Delphi can provide specialized processing services. It makes the membership more attractive.

Looking at global innovation trends, we see an increasing interaction between the development and deployment of new concepts. Practical experience shows that this way of working significantly accelerates the innovation path, decreasing the time between the birth of an idea and the start of commercial use. Looking also at the need of applying the Delphi algorithms to a variety of field data at an early stage, we have started to establish a company Delphi Studio for Imaging that is specialized in processing field data with Delphi technology.

We aim at a cyclic interaction between the Delphi Consortium and the Delphi Studio (see **Figure 10 - 1).** With such an interaction, we can apply Delphi concepts to field data without directly disturbing the research projects. In addition, we can feedback the experience in the Studio to the research teams. In this way we expect to better connect science with business.

Figure 10 - 1 shows the principle. We have started with providing services in the following topics:

1. Deblending and interpolation beyond aliasing

2. Estimation of primaries, removal of surface and internal multiples

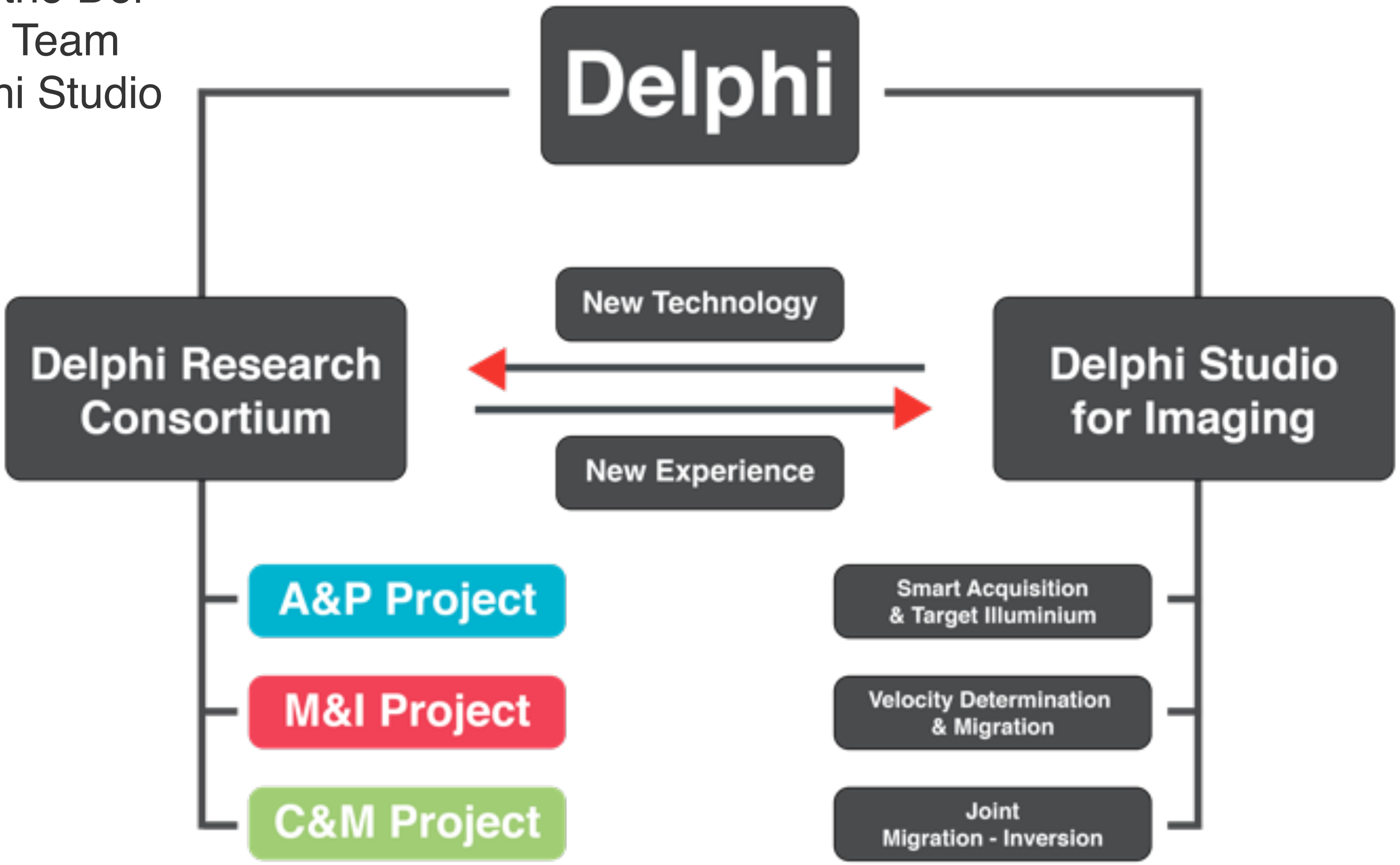
3. Full wavefield migration, using all multiples in the migration scheme

4. Velocity model estimation using joint migration-inversion

The Studio resides close to the campus of the Delft University.

Next page to see figures

Figure 10 - 1: Interaction between the Delphi Research Team and the Delphi Studio for Imaging.



International recognition

11

The work of Delphi scientist has obtained international recognition

International recognition

1981 - Schlumberger Award EAGE (Dr. A.J. Berkhout)

The Schlumberger Award is presented to a member of the EAGE who has made an outstanding contribution over a period of time to the scientific and technical advancement of the geosciences, particularly geophysics.

1993 - Honorary Membership SEG (Dr. A.J. Berkhout)

Honorary Membership is conferred to a person who made distinguished contributions, which warrants exceptional recognition to exploration geophysics or a related field or to the advancement of the profession of exploration geophysics through service to the Society.

1997 - J. Clarence Karcher Award (Dr. D.J. Verschuur)

The J. Clarence Karcher Award is given by the SEG in recognition of significant contributions to the science and technology of exploration geophysics by a young geophysicist of outstanding abilities.

2001 - Distinguished Achievement Award (Delphi team)

This SEG award is given for continuous outstanding achievements in Geophysics by an organization.

2003 - Maurice Ewing Medal (Dr. A.J. Berkhout)

The Maurice Ewing Medal is the highest award of the Society of the Exploration Geophysicists presented to a person who has made major contributions to the advancement of the science and profession of exploration geophysics.

2006 - EAGE Honorary Membership (Dr. A.J. Berkhout)

Honorary Membership is conferred upon a person who has made a highly significant and distinguished technical and/or non-technical contribution to the geoscience community at large or to the EAGE in particular.

2006 - Erasmus Award (Dr. A.J. Berkhout)

The Desiderius Erasmus Award is the highest award of the European Association of Geoscientists and Engineers and is presented in recognition of his outstanding and lasting achievements in the field of resource exploration and development.

2006 - Virgil Kauffman Gold Medal (Dr. D.J. Verschuur)

The Kauffman Gold Medal is awarded by the Society of the Exploration Geophysicists to a person who has made an outstanding contribution to the advancement of the science of geophysical exploration as manifested during the previous five years.

Delphi Advisory Board

12

The Delphi research team is advised by an international board of experts

Delphi Consortium

Delphi Advisory Board

To facilitate effective communication with the sponsors, the Delphi Advisory Board (DAB) has been founded. The DAB consists of senior members of the sponsoring companies and assists the project directors on matters that are at the interface of science and industry. The DAB also advises in efforts to realize a healthy growth of the consortium.

Today, the Delphi Advisory Board is chaired by Professor Berkhout and consists of the following industry members:

Members :

- Craig Beasly - Schlumberger
- Panos Kelamis - Saudi Aramco
- Fiona Dewey - Wintershall
- Roald van Borselen - PGS
- Chris Krohn - ExxonMobil
- Fons ten Kroode - Shell
- Thierry Brizard - CGG
- Paul Meldahl - Statoil
- Walter Rietveld - BP

Honorary Members :

- Mohamed Madidi - retired Exxon Mobil
- Bruce VerWest - retired CGG
- David Wilkinson - Chevron

Sponsorship fees

13

Delphi members pay a yearly fee for each project. There is a one-time entry fee

Delphi Consortium

Sponsorship fees

The annual fee for sponsoring Delphi is as follows:

Sponsor Fees

- One Project: US$ 30,000
  US$ 15,000 late entry fee
- Two Projects: US$ 45,000
  US$ 22,500 late entry fee
- Three Projects: US$ 55,000
  US$ 27,500 late entry fee

The sponsorship is valid for one calendar year and will be renewed automatically each year, unless the sponsor wishes to terminate it. Furthermore, by entering Delphi the sponsor gets access to all previously developed software (source code) and Delphi reports of the last 10 years. The software can be used for evaluating the Delphi algorithms, for in-house processing and for conducting services to the industry. However, the Delphi software cannot be sold or given to third parties.

Sponsorship fees

Appendix A: List of Delphi sponsors

Sponsoring Companies	A&P	M&I	C&M	Sponsoring Companies	A&P	M&I	C&M
Anadarko Petroleum Corporation	■	■	■	Petrobras	■	■	■
BGP	■	■	■	Petronas	■	■	■
BHP Billiton	■	■		PGS	■	■	■
BP	■	■	■	PSS-Geo		■	
CGG	■	■	■	Saudi Aramco	■	■	■
Chevron	■	■	■	Shell Intl. Expl. & Prod.	■	■	■
ConocoPhillips	■	■		Spectrum Geo Inc.	■	■	■
DEA		■	■	Statoil	■	■	■
Delft Inversion			■	TEEC		■	
DMT Petrologic GmbH		■		TGS	■	■	
Dolphin Geophysical	■	■		TNO-NITG	■	■	■
ExxonMobil	■	■	■	Total	■	■	■
Fairfield / Nodal	■	■		Tullow Oil	■	■	■
GDF Suez	■	■	■	Western Geco	■	■	■
INPEX	■	■	■	Wintershall	■	■	■
ION/GX Technology	■	■		Z-Terra Inc.		■	
OMV	■	■	■				

Appendix B: Delphi

1. C.P.A. Wapenaar, 1986, Pre-stack migration in two and three dimensions. (cum laude)
2. A.J.W. Duijndam, 1987, Detailed Baysian inversion of seismic data. (cum laude)
3. P.M. van der Made, 1988, Determination of macro subsurface models by generalized inversion.
4. G.L. Peels, 1988, True amplitude wave field extrapolation with applications in seismic shot record redatuming.
5. N.A. Kinneging, 1989, Three-dimensional redatuming of seismic shot records.
6. G. Blacquière, 1989, 3-D wave field extrapolation in seismic depth migration.
7. A. van der Schoot, 1989, Common reflection point stacking, a macro model driven approach to dip moveout.
8. A.C. Geerlings, 1990, Adaptive Tracing in Seismic Exploration.
9. G.J. Lörtzer, 1990, An integrated approach to lithological inversion. (cum laude)
10. H.C.L. Cox, 1990, Estimation of macro velocity models by wave field extrapolation.
11. D.J. Verschuur, 1991, Surface-related multiple elimination, an inversion approach. (cum laude)
12. J.C. de Haas,1992, Elastic Stratigraphic Inversion, an Integrated approach.
13. Ph. Herrmann, 1992, Decomposition of multi-component measurements into P and S waves.
14. G.C. Haimé, 1992, Downward extrapolation of multi-component seismic data.
15. C.G.M. de Bruin, 1992, Linear AVO inversion by prestack depth migration.
16. B.A. Scheffers, 1993, Near surface seismic imaging.
17. W.E.A. Rietveld, 1995, Controlled illumination in prestack seismic migration.
18. E.J.M. Giling, 1995, Crosswell Seismic Tomography and Migration, Delft.
19. J.W. Thorbecke, 1997, Common Focus Point Technology.
20. F.J. Herrmann, 1997, A scaling medium representation, a discussion on well-logs, fractals and waves.
21. R. Ala"ï, 1997, Improving predrilling views by pseudo seismic borehole data.
22. M.M.N. Kabir, 1997, Velocity estimation of the complex subsurface using the CFP technology.
23. F.J. Dessing, 1997, A wavelet transform approach to seismic processing.
24. A.J.W. van Wijngaarden, 1998, Imaging and Characterization of angle-dependent seismic data.
25. F.J.P.C.M.G. Verhelst, 2000, Integration of seismic data with well-log data. (cum laude)

Appendix B: Delphi

26. R.F. Hegge, 2000, Seismic macro model estimation by inversion of focusing operators.
27. M.A. Schonewille, 2000, Fourier reconstruction of irregularly sampled seismic data.
28. K.M. Schalkwijk, 2001, Decomposition of multicomponent ocean-bottom data into P- and S-waves.
29. A.W.F. Volker, 2002, Assessment of 3-D seismic acquisition geometries by focal beam analysis. (cum laude)
30. E.J. van Dedem, 2002, 3D surface-related multiple prediction.
31. J.F.B. Bolte, 2003, Estimation of focusing operators using the Common Focal Point method.
32. B.E. Cox, 2004, Tomographic inversion of focusing operators. (cum laude)
33. P.M. Zwartjes, 2005, Fourier reconstruction with sparse inversion.
34. E.J. van Veldhuizen, 2006, Integrated approach to 3-D seismic acquisition geometry analysis. (cum laude)
35. S. Tegtmeier-Last, 2007, Redatuming of Sparse 3D Seismic Data.
36. C.O.H. Hindriks, 2007, Estimation and removal of complex near surface effects in seismic measurements.
37. M.N. Al-Ali, 2007, Land seismic data acquisition and preprocessing an operator solution to the near-surface problem.(cum laude)
38. M.J. van de Rijzen, 2007, Estimation of focusing operators for 3D seismic data.
39. J.R. Rommelse, 2009, Data assimilation in reservoir management.
40. J. Przybysz-Jarnut, 2010, Hydrocarbon reservoir parameter estimation using production data and time-lapse-seismic.
41. G.J.A. van Groenestijn, 2010, Estimation of primaries and multiples by sparse inversion.
42. A.R. Ghazali, 2011, True-amplitude seismic imaging beneath gas clouds.
43. A.K. Dey, 2011, Quantitative seismic amplitude analysis.
44. D.A. Chitu, 2011, Iterative inversion of focusing operators.
45. M. Wirianto, 2012, Controlled-source electromagnetics for reservoir monitoring on land.
46. A. Mahdad, 2012, Deblending of seismic data.
47. P. Doulgeris, 2013, Inversion methods for the separation of blended data.
48. P.R. Haffinger, 2013, Seismic broadband full waveform inversion by shot/receiver refocusing.
49. H. Kutscha, 2014, The double focal transform and its application to data reconstruction.
50. A. Soni, 2014, Full wavefield migration of vertical seismic profiling data.
51. T. Ishiyama, 2015, Surface-wave separation and its impact on seismic survey design.

Appendix C: Summary of Delphi Software Releases

The Delphi software releases consist of a package of programs and subroutines, written in Fortran and C, which are tested on the most popular computer systems. The software can be used in combination with the Seismic Unix software, which is free available from Colorado School of Mines.The software includes user manuals and demo scripts, and is distributed to the sponsors via a (protected) FTP site. Some software modules have also been integrated in the processing package Promax.

Currently, the following software is available (release 4 - 5):

General (all projects)

- General file manipulation programs
- 2D multi-offset modeling (finite difference, wavenumber domain)
- 3D multi-offset modeling (finite difference, wavenumber domain, plane dipping reflector ray-tracing)
- One-way focusing operator modeling (Eikonal solver, f-x extrapolation)
- Fourier, Radon and Wavelet transformation
- Radon filtering (linear and parabolic)
- Least-squares subtraction
- Missing (near) offset interpolation using the parabolic Radon transform

Design of data acquisition systems (A&P project)

Focal beam analysis:

- 3D acquisition geometry analysis using focal beams

Appendix C: Summary of Delphi Software Releases

Pre-processing algorithms (A&P project)

Interpolation and regularization:
• 2D and 3D Fourier reconstruction using a sparseness constraint
• Interpolation beyond aliasing using the focal transform

Amplitude pre-processing:
• 2D and 3D acoustic and elastic multi-component decomposition of ocean bottom data

Deblending algorithms:
• Deblending by iterative subtraction of predicted blending noise

Near surface processing:
• Estimating 2D/3D near surface propagation operators by genetic algorithm
• Near-surface redatuming using estimated propagation operators
• Joint Migration-Inversion for near-surface applications

Removing and using multiples (M&I project)

Multiple removal:
• 2D Surface-Related Multiple Elimination (SRME) (shots, CMP)
• 3D pre-stack SRME using sparse inversion for Fresnel zone reconstruction
• 3D pre-stack SRME using differential NMO interpolation (demo version)
• 2D pre-stack internal multiple removal (shots/CMP gathers)
• Multiple removal in the inverse data space
• 2D Estimation of primaries using sparse inversion (EPSI) for surface and internal multiples
• 2D estimation of primaries by Focal transform-based Closed-loop SRME (FCL-SRME)

Appendix D: Capita Selecta of Delphi

Delphi PROJECTS – PUBLICATIONS

The research results of the Delphi consortium are written in a yearly report, one for the A&P project, one for the M&I and one for the C&M project. These reports are only available to the sponsors.
In addition, below a list of key Delphi publications is given that are available in the open literature.

1. Operator Formulation and seismic wave theory (general)

Berkhout, A. J., 1981, Wave-field extrapolation techniques in seismic migration - A tutorial: Geophysics, 46, 1638-1656.

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