The role of potential fields as an early dataset to improve exploration in frontier areas

Phill Houghton[1*], Peter Nuttall[1], Milos Cvetkovic[1] and Stanislaw Mazur[2] discuss the role potential field data can play in improving and accelerating exploration in frontier areas, such as North East Greenland.

One of the last frontier exploration areas that remain are the basins located in the Arctic. The US Geological Survey (2008) has estimated that the areas to the north of the Arctic Circle could hold as many as 134 billion barrels of recoverable hydrocarbons. The East Greenland Rift Basins Province alone is estimated to contain approximately 31,400 MMBOE (USGS fact sheet 2007-3077).

While the size of the prize is immense, operators face many challenges, such as sea ice, icebergs, scarcity of data, and environmental sensitivity which can result in high finding and development costs. Therefore, exploration decisions should employ the best practices and application of tools that reduce uncertainty and lower exploration risk.

The application of potential field data as a regional screening tool for basement mapping and basin definition is well-known and seismic acquisition routinely acquires shipborne gravity and magnetic data for such purposes. Recent advances in airborne gravity gradiometry (DiFrancesco, 2009) provide explorationists with a new tool that can be successfully integrated into the exploration workflow.

In this article we will review the applicability of various potential field acquisition methods and demonstrate how the data can be integrated with 2D seismic data to provide a better geologic understanding of a frontier region such as North East Greenland. We also will provide an insight into how it is possible to integrate all available information to help unlock the exploration potential in the Arctic.

Application of airborne gravity gradiometry in frontier basins

The 2012/2013 North East Greenland licence round blocks cover an area of 50,000 km^2 with the centre of the licence blocks over 700 km from Longyearbyen, Svalbard. Because of the operational difficulties inherent in marine acquisition offshore North East Greenland, the ideal choice for the collection of potential field data is to acquire it from an airborne platform. In considering the options for airborne data acquisition, the two obvious choices are conventional airborne gravity or airborne Full Tensor Gradiometry (FTG). Several factors such as the minimum recoverable wavelength, signal-to-noise, line spacing, time on task, safety and cost all feed into the decision-making process as to which method to deploy.

Conventional gravity data only measures the scalar quantity Gz, whereas FTG data recovers the nine tensor components of the gravity field (Figure 1).

While theoretically one can forward compute the tensor components from scalar gravity measurements, the 3D nature of FTG measurements yields significant advantages when considering the minimum recoverable wavelength and survey line spacing. The reported resolution of the AIRGrav conventional airborne gravity system at 1km line spacing,

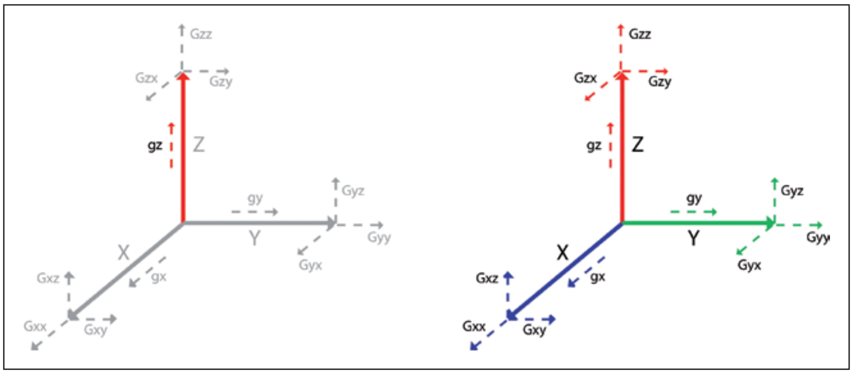

Figure 1 Gravity and gravity gradient measurements.

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at a velocity of 120 knots is 4 km ½ sine wave (source: www.sgl.com), equivalent to a minimum recoverable full wavelength of 8 km. It has been illustrated (Barnes et al., 2009) that due to the FTG measuring the entire gradient tensor at each measurement point, the line spacing of gradiometry surveys can be increased without aliasing and for most cases the grid Nyquist frequency calculated as 1x the line spacing. Therefore in principle, an equivalent survey design could be flown with a FTG system with 50% fewer lines compared to that of a conventional airborne gravity system.

In the case of the North East Greenland airborne FTG survey, the line spacing chosen was 2 km x 10 km, which gave rise to a minimum recoverable full wavelength of 2km. Therefore, when compared with a conventional gravity survey with 1 km line spacing, an airborne FTG survey could be flown with 50% fewer lines and more importantly with a four-fold increase in useable bandwidth. Notwithstanding any bandwidth improvement in the data, 50% fewer lines meant that the survey could be flown quicker and subsequently reduce the overall HSE risk.

When considering the interpretability of acquired data, we need to consider signal-to-noise as well as the useable measurement bandwidth. Wider bandwidth in this context typically means that the interpreter can discern more of the geologic signal. Reviewing the frequency spectrum and signal-to-noise of simulated airborne Gz and Gzz over a real broadband geologic model (Figure 2) it can be seen that at higher frequencies (depicted in red), Gzz has an improved signal-to-noise ratio, whereas at lower frequencies (depicted in green) Gz has an improved signal-to-noise ratio. Therefore, if you wished to recover as much of the earth's signal as possible with the highest signal-to-noise, a combination of both Gzz and Gz measurements would yield the optimal dataset. This is something that can be readily achieved on a single acquisition platform and in the case of the North East Greenland FTG survey both measurements were captured during acquisition.

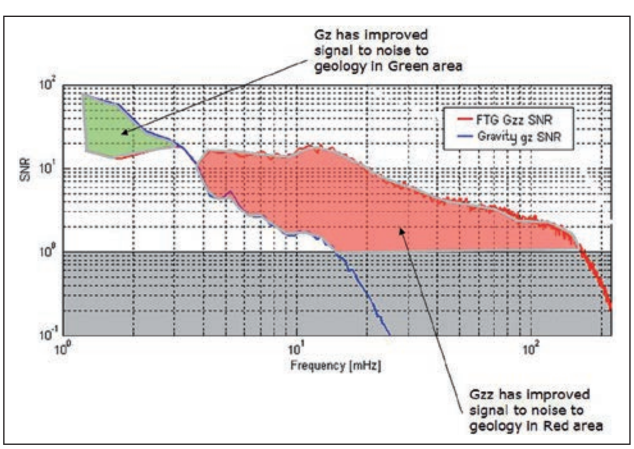

Figure 2 *Signal-to-noise ratio (SNR) along a survey line (62 m/s) flying over a wide bandwidth geologic model. Gzz deduced from FTG measurements, Gz deduced from airborne gravity measurements.*

The selection of survey line spacing is typically made based on the resolving power of the instrument and the results of feasibility modelling, where the explorationist can test the capability of a technique against an inferred input geologic model. In the case of frontier exploration, the survey line spacing is typically fairly wide, i.e., ≥ 4 km, which as discussed previously, means that the minimum recoverable wavelength will be long, lower resolution, and, used for the identification of large-scale features. The deployment of FTG technology means that a survey can now be designed to recover a much wider bandwidth and consequently more of the geologic signal. Survey designs that are at a regional line spacing (i.e., 2 km) such as the survey flown in North East Greenland means that at typical survey speeds (62 m/s) the survey will be able to capture data out to 31 mHz (1 mHz = 0.001 Hz). In the case of the simulation shown in Figure 3, 31 mHz highlights that a significant portion of the geologic signal would be measured with a signal-to-noise ratio greater than 10, whereas the Gz gravity signal is decaying rapidly and falling below 1 at 15 mHz. While the FTG instrument is capable of much wider bandwidth, in North East Greenland this was not exploited. However, the bandwidth of the final gridded data could be further upgraded, if desired, by infilling the survey with a tighter line spacing (e.g., 500 m) over those areas that were of specific exploration interest.

The resultant high resolution, wide bandwidth data does not come without additional challenges. The non-uniqueness of potential field data means that interpreting the data requires additional constraint and robust integration if the data is to be fully utilised.

Data comparisons

In North East Greenland prior to the collection of the airborne FTG survey, conventional marine gravity and magnetic data were acquired along with the 2D seismic programme. The resolution of all dynamic gravity systems is limited by the necessity to remove unwanted vertical accelerations which, due to the equivalence principle, contaminate the measured gravity signal. The removal of this error in the marine environment is achieved by the application of low pass filtering with a time constant between three and five minutes (Dodson et al., 1997). At typical survey speeds this represents a distance of 0.5-0.9 km. Additional filtering applied during data processing means that the typical resolution of the final reduced profile data can be as high as 1.5 km-3 km full wavelength; however, due to the anisotropic nature of 2D seismic surveys the resultant gridded data is lower resolution. To illustrate the varying resolution and usefulness of data, a comparison between public domain satellite data, marine gravity data and airborne gravity data from the FTG survey is reviewed.

Figure 3 displays the satellite gravity signal over the North East Greenland survey area. The data appears stip-

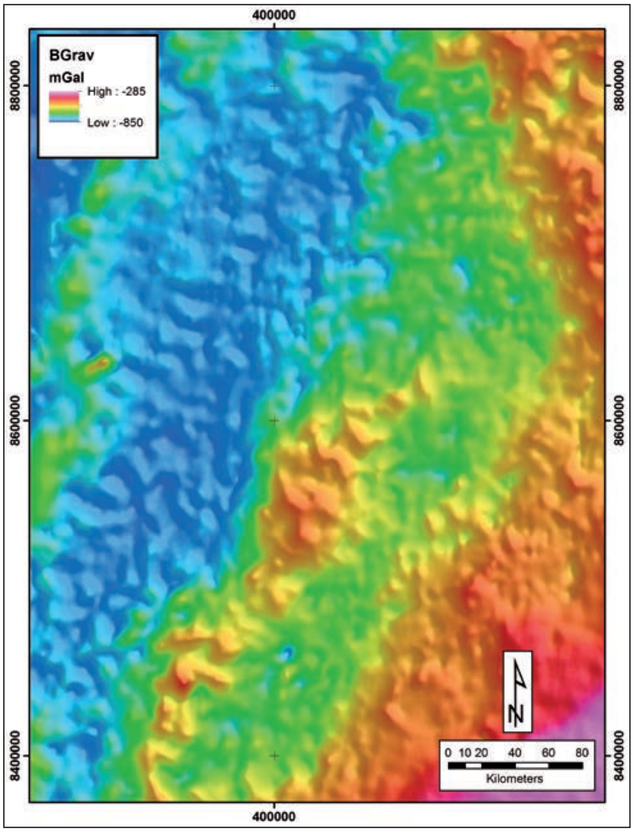

Figure 3 *Public domain satellite gravity data.*

pled – which is largely due to the amount of noise present in the data, but large-scale features are discernable in the data. For example the expression of the Danmarkshavn Ridge is becoming evident in the centre of the image.

In the case of the marine Bouguer gravity data seen on the left of Figure 4, although the survey data has been downgraded by gridding as a result of the anisotropic nature of the acquisition, the signals are more coherent. The expression of the Danmarkshavn Ridge is clearer and additional filtering of the data (i.e., high-pass) would allow the interpreter to extract more useful geologic information at a basin scale.

The equivalent gravity signal derived from the airborne FTG survey is shown on the right of Figure 4. The uplift in the data is significant, and due to three factors: the increased spatial sampling of the survey (2 km x 10 km) compared to the previous examples; the improved signal-to-noise inherent in the data, and the resultant increase in bandwidth afforded by the FTG system. The amount of useful geologic information that can be gleaned from the data is clearly evident and will allow the interpreter to build a more detailed picture of the main tectonic elements in the region. For example, the spatial distribution and extent of the salt bodies in the basin to the north is now very accurately defined.

The use of potential methods to better understand salt geometries and deliver an improved understanding of the earth model is well known. Stadtler et al., (2010) demonstrated the impact of integrating all available data to image salt in the Nordkapp basin, Barents Sea. The data showed that the geometries of diapirs and thickness of autochthonous salt and cap rock could be resolved within an uncertainty range. In addition, it highlighted that the development of a robust crustal model impacted the interpretation of the basement and salt surfaces. The results obtained from the work enabled the company to partly relinquish acreage and help plan future 3D seismic acquisition.

The work carried out in the Barents Sea benefited from having 3D seismic data, gravity data, magnetic data, EM data, and marine FTG data over the area of interest and

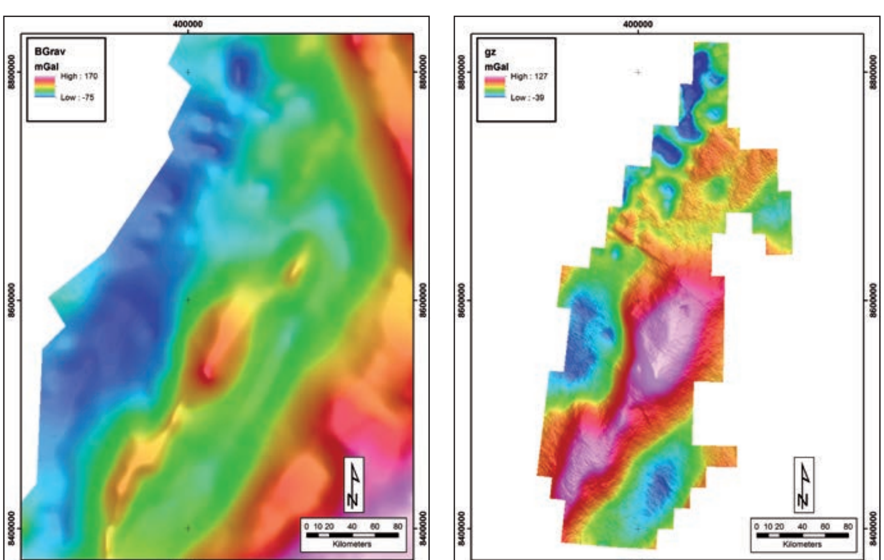

Figure 4 *Marine Bouguer gravity data (left) and Gz derived from the airborne FTG survey (right).*

highlighted the value of data integration. It also served to demonstrate the importance of building a robust structural model throughout the entire depth section, an area where potential field data plays an important part. However, in frontier areas that are underexplored such as North East Greenland, 3D seismic data is yet to be acquired and further geological interpretation is needed before planning expensive 3D seismic programmes. 2D seismic data is routinely acquired in frontier basins but irrespective of how careful the design and layout of a 2D programme, limitations and compromises will exist. For example, any given 2D line may miss or clip a structure, which in turn, could lead to a misleading interpretation.

Modern processing and velocity model building solutions help to improve some of the issues inherent in 2D data acquisition. For example, the application of Apex Shifted Multiple Attenuation (ASMA) routines (Stewart et al., 2007), which are able to capture and remove out-of-plane events, are especially critical. The removal of spurious noise, without impacting the true in-plane data, is critical prior to attempting any pre-stack time and depth imaging. Therefore, having an independent measurement of the spatial location and geometry of fault and salt features can add significant confidence to the velocity model building process and subsequent depth imaging and regional interpretation.

In North East Greenland, the extent of the salt basin can be clearly seen in the FTG data and further examination of the 2D seismic line layout highlights many of the problems when designing a survey and subsequently interpreting the data. Figure 5 shows that the western portion of the seismic line runs between two large offline salt features separated by only 6 or 7 km (blue outlined shapes).

The seismic data processing of the North East GreenlandSPAN data has benefited from the application of ASMA routines. However, at the time of the initial migration-to-depth, the airborne FTG data was not available. In reviewing the velocity model for the line (Figure 6), salt has been interpreted in this complex section.

If the seismic imager and interpreter had been provided with the FTG data during the model building stage the interpretation of salt from the 2D profile could have been recognized as out-of-plane energy from the adjacent salt bodies, and could have arrived at a different velocity model.

In an ideal scenario, the airborne FTG data would have been available to the seismic processors at the beginning of the imaging process. However, the only data available in this instance was the marine gravity data acquired along the 2D seismic lines. As shown previously (Figure 4) these data do not have the spatial resolution to clearly identify out-of-plane features. Additional data processing could be applied to the seismic data to improve the image, but care needs to be taken in the various approaches deployed. Targeted filtering of the gathers to remove obvious out-of-plane effects or 'noise' in the data could also impact the underlying primary signal. Applying high-end migration algorithms such as Reverse Time Migration (RTM) on the data will produce an alternate image for interpretation but the gains will depend on the problem at hand. In the case of the seismic line in figure 7 the velocity of the salt is close to that of the surrounding sediments and, while there are improvements to the final seismic image, the 2D nature of the profile adjacent to large salt bodies is the primary factor limiting the interpretation at this location.

Figures 4 and 5 highlighted the additional information that can be obtained from the FTG data during the qualitative interpretation phase. The delineation of the salt distribution in the salt basin to the north is clear, and the improved definition of the main sedimentary basins and positioning of major fault boundaries enables the interpreter to build a more accurate tectonic elements map. However, in order to extract more from the data beyond qualitative interpretation, it is necessary to perform quantitative modelling in the form of 2D/2.5D forward modelling and 3D inversion.

Data integration and quantitative modelling

In order to extract the maximum value from potential field data the non-uniqueness needs to be constrained with *a prio-*

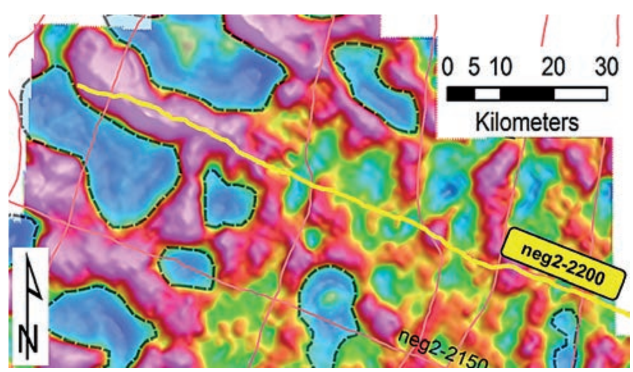

Figure 5 *Survey line layout superimposed on Gzz data and salt interpretation.*

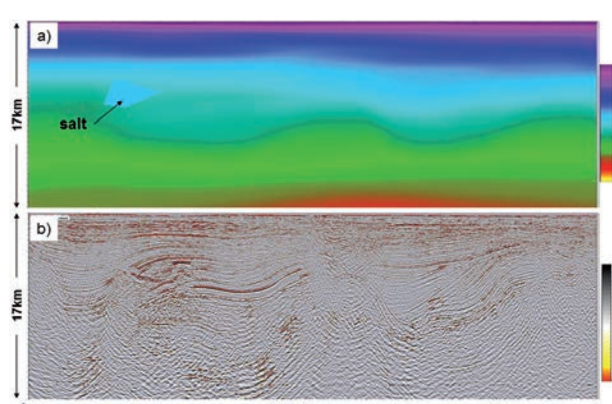

Figure 6 *Seismic velocity model shown above Kirchhoff PSDM migrated seismic image.*

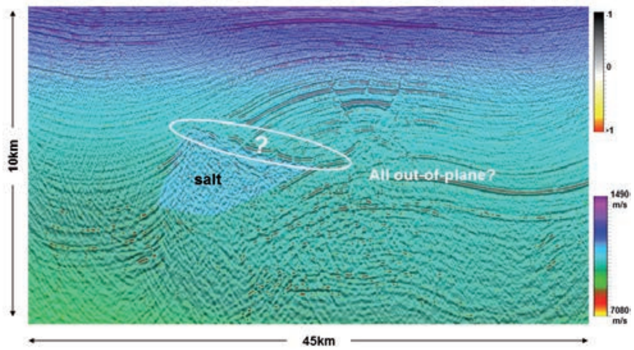

Figure 7 *Seismic velocity model superimposed on Kirchhoff PSDM seismic image.*

ri information. In the case of the data acquired in North East Greenland, the project benefited from 32 seismic sections that crossed the 2012/2013 licence blocks and lay within the airborne FTG survey area. For each seismic line modelled, the following data were available to the interpreter: marine gravity data, marine magnetic data, airborne FTG data, airborne magnetic data, and bathymetry data. Due to the lack of fathometer data coverage in the area, care was taken to derive a suitable bathymetric surface which could be used for data reduction and modelling. In this instance the contractor, ARKeX, constructed a database that combined the International Bathymetric Chart of the Arctic Ocean v3 (IBCAO) with all available data from the seismic survey. The database was analysed and further processed to deliver an improved bathymetric grid for the survey area.

Prior to commencing the quantitative modelling a regional Moho surface (Figure 8) was generated from the 3D inversion of Bouguer gravity data, which was further depth constrained by two refraction lines AWI 2003 0500 and AWI 2003 0400 (Voss and Jokat, 2007). The resultant surface was used as a starting point to constrain the Moho in 2D gravity forward models along the seismic lines. The seismic data interpretation was reasonably well constrained in the shallow part of the section where coherent seismic reflectors could be picked. However, deeper in the section and around the areas of salt, the seismic interpretation was less certain and the combination of gravity and magnetic data was used to help create/update horizons. Thirteen stratigraphic horizons were included in the modelling and tied to provide a consistent geologic framework that honoured all available data. An example of a 2D/2.5D model iteration from North East GreenlandSPAN is shown in Figure 9. This iteration of the model shows the calculated response (red profiles) against the actual profile data (blue profiles). The profiles shown in the model window are from the top: airborne FTG data (Gzz); marine gravity data (gz); and marine magnetic data. The marine data extended beyond the coverage of the airborne FTG data and, in this example, the FTG data shows there is an additional signal that can be interpreted and

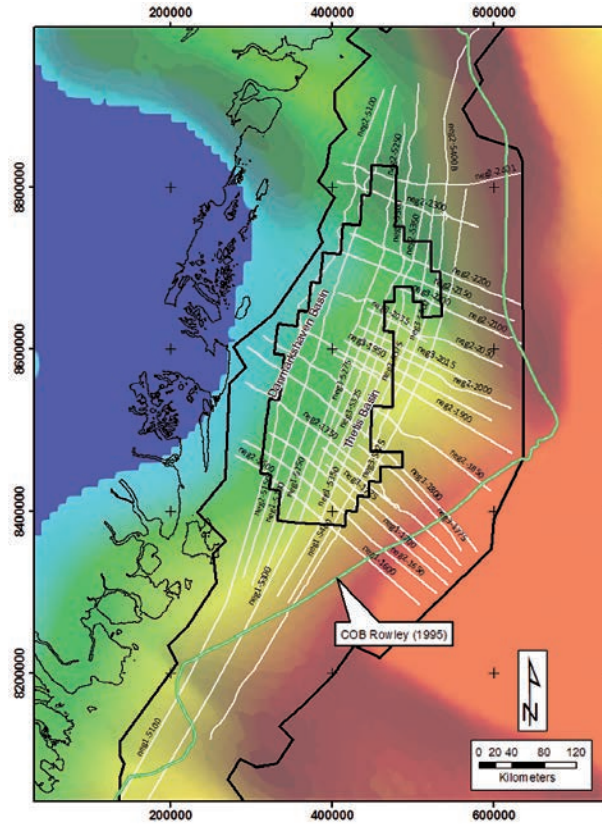

Figure 8 *Moho Surface created from Bouguer gravity data.*

illustrates the higher bandwidth available when compared to the conventional data.

Having developed a consistent framework of 2D and 2.5D models the next step is to generate the 13 horizons in 3D and forward compute the model response to determine the degree of fit to the observed gravity and magnetic data. Any residual errors found should be analysed and used to further guide the interpretation until such time that the error converges and is within the respective tolerances of each dataset.

The character of the seismic data clearly shows evidence of salt to the north of the survey area. The geometry and location can be misinterpreted due to offline effects in the seismic data and, given the density of lines, it is difficult to get a good measure of the spatial extent of the salt in the basin. Using the qualitative interpretation of the FTG data, it is possible to accurately outline the spatial extent of the salt and incorporate this information into the 3D modelling workflow. As indicated in Figure 5, the outline of the salt features can be digitised to create a salt mask which is then used in the 3D modelling to provide what is effectively a salt flood, whereby the amount of salt to satisfy the residual anomalies present in the data is included in the model. This is a first order approximation of the salt volumes present and does not take into account any complex morphology. Further

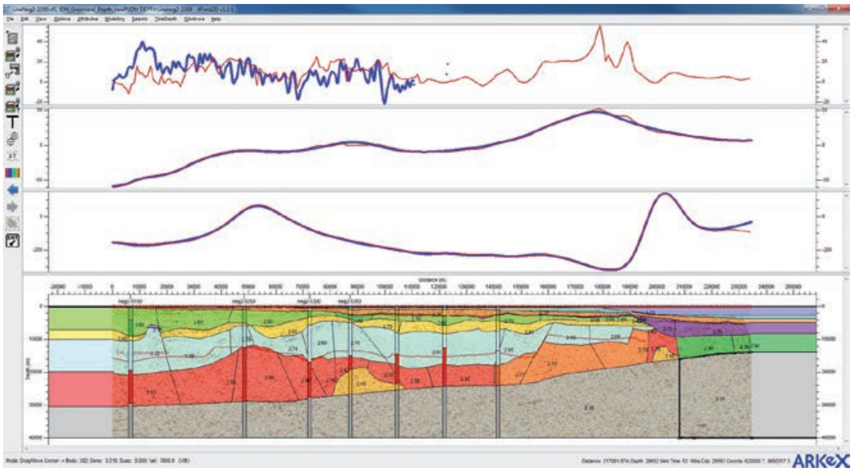

Figure 9 *Iteration of 2D forward modelling of seismic line from North East GreenlandSPAN with intersecting 2D models.*

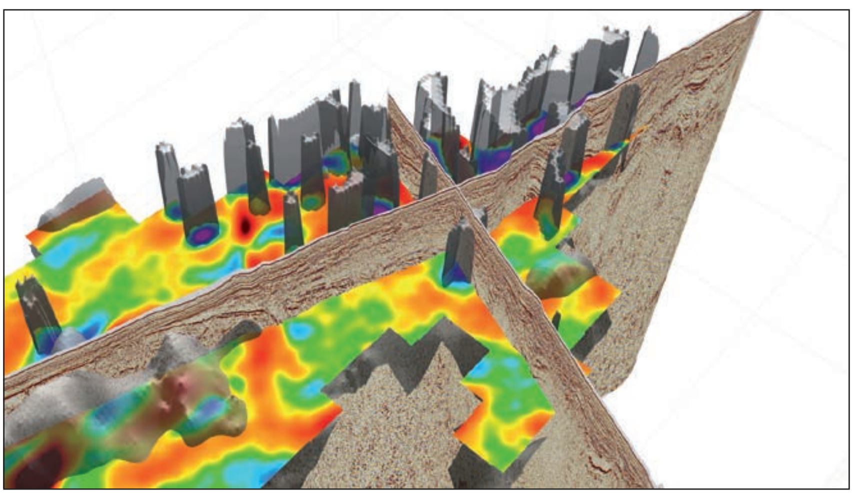

Figure 10 *Salt flood surface (grey) shown together with Gzz grid and seismic data.*

modelling in 2D/2.5D can be used to test the morphology of the salt shape as well as testing for possible variations to salt density (i.e., due to the presence of anhydrite or other evaporites). An example showing the extent of the salt and the initial salt flood put into the model is shown in Figure 10. A critical strength of the process is an improved understanding of the spatial extent of the salt and the amount of salt present where the seismic line intersects a salt body as well as the effects of salt features present offline.

The quantitative modelling and integration with 2D seismic data is an iterative process that involves close collaboration with the structural geologist and geophysicist to ensure a geophysically consistent and accurate geologic model is developed.

Conclusion

In frontier areas, such as the Arctic, accessing the huge resource potential comes with significant exploration challenges. The challenge faced by operators is how to explore efficiently and deploy the appropriate technology at each stage of the exploration process.

Potential field data is often used as a regional screening tool. However, airborne gradiometry can provide a high resolution dataset with increased bandwidth, a smaller acquisition footprint and reduced HSE exposure. Combined with a regional 2D seismic programme, it provides a powerful step to reduce uncertainty in frontier exploration and focus on the next phases of 3D acquisition. If airborne gravity gradiometry data was available prior to the planning of the 2D seismic acquisition the line layout of the North East GreenlandSPAN data may have been altered, especially in the salt basin to the north.

Determining salt geometries using 2D seismic data is challenging due to the nature of acquisition. Integration of gravity data to reduce interpretation uncertainty, particularly in areas of salt, is an area of integration that will benefit from further development. The availability of improved modelling tools, better integration of data to identify offline effects, improved velocity model building, and updated processing routines will help to improve the confidence of the seismic interpretation and reduce overall exploration uncertainty.

In North East Greenland, integration of FTG data at various stages of the interpretation has enabled the geologists to further refine their overall interpretation and geologic understanding of the North East Greenland province. The result is a geophysically consistent geologic model that honours all the currently available data. The geologic models can be further constrained/upgraded by the acquisition of additional data, which could provide more constraint and allow testing of different geologic assumptions. Any future models should be validated against the potential field data to ensure that future interpretations are consistent with all data.

The application of new technology with increased data resolution and bandwidth is playing an important role in frontier areas. Data integration is a critical component to its success but does not come without technical challenges. Projects like North East Greenland, and others where Ion has incorporated FTG technology, indicate that potential field data will continue to be a valuable and cost-effective component in the overall exploration workflow for some time to come.

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