First Break Special Topic

Near Surface Geoscience

Our Special Topic this month provides an opportunity to focus exclusively on interesting and innovative developments in near surface geoscience, and in the process provide a foretaste of the EAGE's annual Near Surface event being held this year in Leicester, UK. Hopefully we can be forgiven for offering the spotlight to locally based authors, especially as our introductory piece from John Reynolds provides a masterful overview of mainstream near surface geoscience applications plus some observations on the direction that these technologies may take in the future.

Meantime Wilkinson et al. report on progress with automated time-lapse geoelectrical monitoring of land environments liable to instability which are being carried out by the British Geological Survey. This is the kind of science endeavour which regrettably is invisible to the community at large, yet plays an important role in public safety.

Cassidy et al. provide some challenging reflections on assumptions made about the limitations of ground penetrating radar (GPR). They show in some detail that for non-destructive testing of concrete structures an appropriately applied combination of GPR and ultrasound can be effective in many more scenarios than commonly thought.

Our last contribution from Strobbia et al. is a reminder that oil and gas E&P has its near surface issues, in this case, dealing with surface waves in land seismic acquisition.

Special Topics	
January	*Data Management + Carbon Capture and Storage*
February	*Land Seismic*
March	*Modelling/Interpretation*
April	*EM/Potential Methods*
May	*Unconventional Resources and the Role of Technology*
June	*Rock Physics & Formation Evaluation*
July	*Well Technology + Passive Seismic*
August	*Near Surface Geoscience*
September	*Data Processing*
October	*Reservoir Geoscience and Engineering*
November	*Petroleum Geology and Basins*
December	*Marine Seismic*

More Special Topics may be added during the course of the year.

Developments and future trends in near surface geophysics

Prof John M. Reynolds* reviews where near surface geophysics and its various sub-disciplines are today and the challenges ahead, based upon work preparing a second edition of his well-known textbook on environmental geophysics.

As a consequence of writing a much expanded and revised second edition of my environmental geophysics textbook (Reynolds, 2011) I have had the opportunity of seeing how near surface geophysics has changed over the 15 years since I prepared the first edition (Reynolds, 1997). It has been possible to identify new sub-disciplines emerging and new opportunities for cross-sector transfer of technologies, as well as developing trends. This overview was also helped by attending the Symposium on Applied Geophysics in Environmental and Engineering Projects (SAGEEP), held in April 2011 in Charleston, South Carolina, USA.

It is clear that much has changed, mostly for the better; more people have been writing about what they have been and are doing so that the published literature is far more extensive now than two decades ago. Not only are there many more papers but also the number of specialist journals is growing. It makes it increasingly difficult for one person to have a clear overview of the entire subject. Consequently, my comments on changes, trends, gaps, and problems within the near surface sector reflect my own personal experience within both the academic and commercial communities.

I have been indebted in my preparation of the second edition to colleagues throughout the world who have so kindly and freely provided material and thereby guided my overview of the subject. What follows is just a summary of some of the issues that I have identified. More details of the techniques discussed can be found in the second edition of my book.

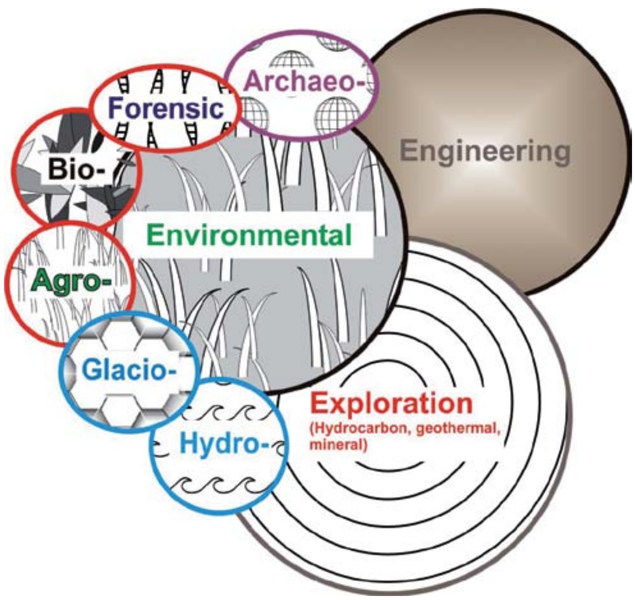

Figure 1 *Inter-relationships between the various sub-disciplines of applied geophysics. Those circled in red are new compared with 1995. (Adapted from Reynolds, 2011).*

New sub-disciplines of applied geophysics

The various sub-disciplines currently in applied geophysics are shown in Figure 1. By far the largest, most extensive, and most mature is resource exploration, especially for hydrocarbons and minerals. Environmental and engineering geophysics have been in development increasingly since the 1960s and especially so over the last two decades, so need little introduction.

Also included in Figure 1 are six other sub-disciplines. Of these three have become well established through to the 1990s: archaeo-geophysics (geophysics in archaeology); glacio-geophysics (geophysics in glaciology) and hydro-geophysics (geophysics in groundwater investigations). Glacio-geophysics is particularly well established within the polar scientific communities and has been since the 1950s. The application of ground-based geophysical techniques for glaciological studies (and especially on temperate glaciers) has come of age especially since the early 1990s. This has been a result of better availability of both improved and more field-portable commercially available equipment. A natural development of this application is the use of geophysical techniques to investigate permafrost (Hauck and Kneisel, 2008). The investigation of the cryosphere has long been important, especially in the polar regions.

Attention is now being paid to climate change and particularly to the adverse effects it is having, especially in high-latitude and high-altitude environments, where the impacts are being felt disproportionately with respect to other regions. Detailed investigation of frozen ground and massive ice bodies and their thermal and geophysical characteristics

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is vital if the associated underlying physical processes are to be understood. Over the last few years the hydro-geophysics sector has benefited significantly from major advances in helicopter-borne electromagnetic surveying and from the coming of age of magnetic resonance sounding. A useful overview of developments in hydro-geophysics was published in the Special Issue of *Near Surface Geophysics,* 7(5–6), 2009.

Three new sub-disciplines have emerged over the last 15 years: forensic geophysics (the application of geophysical methods to investigations that might come before a court of law); bio-geophysics (geophysical manifestation of microbial activity within geological materials); and agro-geophysics (the use of geophysics for agriculture and soil science). Forensic geophysics is now recognised as a sub-discipline of forensic geoscience ('geoforensics'; see Ruffell and McKinley, 2008) and is used regularly in police investigations in searches for mortal remains, buried bullion, etc. The sub-discipline of bio-geophysics has emerged over the last decade or so (e.g., Williams et al., 2005) and examines the geophysical signatures of microbial cells in the Earth, the interaction of micro-organisms and sub-surface geological materials, and alteration of the physical and chemical properties of geological materials as a result of microbial activity. The microbial activity may be natural, as in microbial bio-mineralization, or artificial as in the insertion of bacteria into the ground to remediate diesel spills, for example. Perhaps the newest branch is agro-geophysics (Lück and Müller, 2009, and other papers in the same issue), which has emerged over the last decade. Recent examples of applications of agro-geophysics include water retention capacity of soils, effects of long-term fertilization on soil properties, and influences of tillage on soil moisture content. One further sub-set of these geophysical applications is in the maintenance of golf courses. In 1996 in the USA alone the annual cost of maintenance of golf courses was estimated at more than $4.5 billion; by 2006, there were over 15,000 golf course facilities in the USA alone, with the number growing all the time. Consequently, there is a significant case for the use of non-invasive geophysical techniques for the investigation of golf courses and, in particular, of tees and greens. To this end electromagnetic conductivity mapping and ground penetrating radar are being used increasingly.

Developing techniques

Over the last 15 years technology in general has changed substantially and geophysics has been no exception. There have been significant advances in specific geophysical methods and the use of wireless technology in data communications (e.g., cable-free geophone spreads; instrument-to-data logger connectivity). We have seen the adoption of magnetic resonance sounding in hydrogeology (e.g. Special Issue of *Near Surface Geophysics*, **9**(2), 2011) and the continuing development of helicopter-based EM (*h*-TEM), particularly in groundwater investigations and in mineral exploration. For instance, in the decade 1997–2007 alone some 18 different *h*-TEM time-domain EM systems and seven frequency-domain systems became operational. During the same period, seven fixed-wing TEM systems and five frequency-domain systems entered service. Helicopter-based multi-sensor magnetometry has become fully commercialized with up to 22 sensors in a horizontal array and can be flown at very low ground clearances (typically ~ 1 m!) for unexploded ordnance (UXO) detection; this complements multi-coil helicopter-mounted EM UXO detection (Figure 2).

Over the last decade marine controlled source electromagnetic (CSEM) methods have moved from proof of concept tests in 2000 through to fully commercialized systems with a number of contractors now offering these services for the hydrocarbon industry. The majority of deployments over the last two years have been 3D surveys. This has the advantage that 3D datasets facilitate a better understanding of the background response and hence reduce the ambiguity inherent in some 2D data sets. Improved spatial sampling, better quality data, and integration with seismic and well-log data are increasing the reliability of marine CSEM surveys.

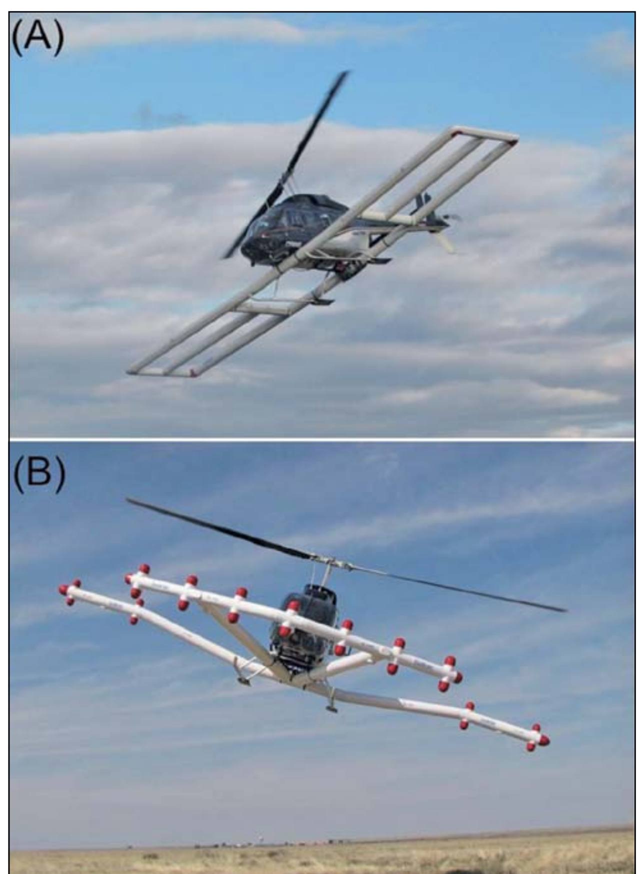

Figure 2 *Airborne UXO-detection systems: (A) Battelle TEM-8 and (B) VG-22 multi-channel gradiometer. Photographs courtesy: Battelle.*

It is critical that the interpretation of CSEM results is undertaken in conjunction with seismic structural information and rock physics. At present much of the data analysis and interpretation is undertaken by specialist geophysical contractors. As experience and confidence in the joint interpretation of both seismic and CSEM data develop it is likely that the integrated interpretation will move more in-house to the oil and gas companies in much the way that seismic interpretation became a distinctly separated process from data acquisition and data processing. The benefits of and trends within marine CSEM surveying have been discussed recently in *First Break*, **29**(4), 2011, for example.

Over the last decade, the use of shear wave seismic techniques by the geotechnical community has increased markedly to investigate voided ground, areas affected by near surface structures, and to determine the shallow shear wave velocity variability for seismic hazard micro-zonation. These methods began to be used in the 1960s but since then, and especially since the mid-1990s, shear wave methods have developed along two paths:

(i)Ground stiffness measurements using (a) Spectral analysis of shear waves (SASW), which uses two to six geophones and a hammer source and more recently (b) Continuous surface wave systems (CSWS), which use a tunable 70 kg source generator and a linear array of typically five geophones;

(ii)Since 1999, multichannel analysis of shear waves (MASW), in which typically 24 or more channels (Park et al., 1999) are deployed with either an active source (e.g., hammer) or passive sources (e.g., traffic noise) or both. Instead of standard fixed geophones, the system can be used with a seismic land streamer for faster ground coverage.

A variant of the passive MASW technique is the refraction microtremor method (ReMi) in which the apparent phase velocities of Rayleigh waves propagating along a linear array of vertical geophones are measured at the ground surface (Louie, 2001). The advantage with this method is that it is ideally suited to urban areas with lots of noise and uses all the same equipment as for a traditional seismic refraction survey with the exception that there is no need for a specific controlled seismic source. ReMI can also cope with velocity inversions unlike the traditional seismic refraction method and can be used to obtain shear wave velocity/depth profiles down to 20 m or more, depending upon ambient conditions. Most recently, Raines et al. (2011) have described a case history in which the method was used very successfully to locate a mineshaft and the edge of a backfilled quarry.

With technological development comes the opportunity to miniaturize sensors and deploy them on ever smaller platforms. Consequently, research is being undertaken into the use of unmanned airborne vehicles (UAVs), very light aircraft (VLA, such as gyroplanes), and (micro-)drones of various types. Once a suitable platform has been developed, the challenge is then to deploy as many different sensor types as possible. One gyroplane system, the GyroLAG, which is flown by a pilot on board, can have seven geophysical sensors deployed simultaneously. These include two three-component fluxgate magnetometers; a portable gamma-ray spectrometer; scalar and vector gravimetry; digital video/aerial photography; a thermal imaging camera; and a laser scanner (Ameglio et al., 2011). Small radio-controlled fixed-pitch multi-bladed helicopters (quadrotors or quadrocopters, with four blades, up to octocopters with eight blades) have been developed on which digital cameras can be mounted for high-resolution aerial photography and covert surveillance. These are currently only able to carry the weight of a digital camera, but it is only a matter of time before the lifting capacity of these UAVs is increased to the point where even smaller geophysical sensors can be deployed. The main benefits of these smaller aerial platforms is the vastly reduced costs of mobilization, maintenance, and operation, and the ability to use them in more restricted locations where the use of helicopters would either be prohibitively expensive or logistically inappropriate. Key applications would be in UXO detection and in agricultural surveys, to name but two. The relative ranges of spatial resolution and costs of deployment for various types of platforms for geophysical sensors are illustrated schematically in Figure 3.

While perhaps not so much fun to operate as quadrocopters and their kind, terrestrial multi-sensor platforms have also been developed, such as the geophysical exploration equipment platform (GEEP), which can be towed by a golf cart or quad bike. For example, two caesium magnetometers and an electromagnetic conductivity meter or dual-coil EM system can be deployed simultaneously (Hill, 2008). Positional information is recorded at the same time through a GPS antenna mounted on the towed platform.

Trends in near surface geophysics

In many cases of environmental and engineering geophysics, the emphasis has for many years been on exploration mapping, with interpretation sometimes limited just to anomaly spotting. This is still the case in low-end mineral exploration.

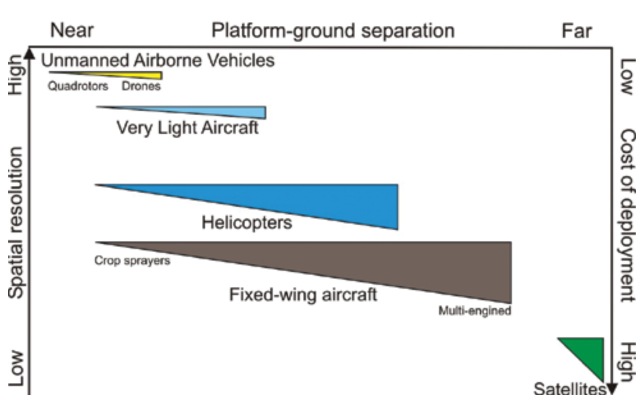

***Figure 3** Schematic showing the relative ranges of spatial resolution and cost of deployment for various types of platforms for geophysical sensors.*

However, as the cost of data acquisition per measurement has fallen dramatically, it has become much easier and more cost effective to gather much more data and with far greater spatial resolution. This has led to the use of repeat surveys over the same profiles after a specific interval of time so that time-variant processes can be monitored, extending the range of surveys from mapping to monitoring. In some situations, such as in landfill sub-liners, multi-electrode arrays are installed at the time of landfill cell construction and used to monitor below the impervious lining to check whether or not leachate is leaking out throughout the lifetime of that cell and perhaps even beyond. Similarly, time-lapse ground conductivity measurements can be used to check on the effectiveness of certain types of bio-remediation of contaminated soils. With the power of modern laptop computers, it is much easier now to be able to plot up and view the data gathered and provide some in-field interpretation.

While new applications are found for existing geophysical techniques by researchers and commercial operators, equipment manufacturers have also helped to create commercial niches. This is best exemplified by ground penetrating radar (GPR) equipment producers. In the 1990s, the range of equipment tended to be classified by whether the application was geological (preferred use of lower frequencies) or engineering (use of higher frequencies). Now specific radar systems (such as proprietary radar carts) are available for particular applications, such as utility mapping, road pavement inspections, and railway track ballast investigations, where the equipment operator does not need to be a qualified geophysicist, but a technician trained in a given application. Companies devoted to those applications are now flourishing.

While some developments have been to match a specific instrument type to a niche application, there is also a trend of increasing the number of complementary methods, not necessarily deployed simultaneously during acquisition but in order to use the results from one method to constrain the analysis of the other. This has been done for many years, especially in higher-end mineral exploration using the range of ground-based (including borehole) and airborne geophysical tools in multi-method surveys (magnetometry, radiometrics, electromagnetics, resistivity, induced polarization). This approach has been further developed by the incorporation of other spatially-rectified data sets, such as remote sensing data (imaging and hyperspectral) and integration of the results in geographical information systems (GIS), for instance, to produce so-called 'data cubes'. These integrated databases (Figure 4) can be analysed in concert with each other to produce a 'knowledge cube' that contains a 3D ground model of geology, structure, material characteristics, etc. The key difference here is that once a viable 3D ground model is produced, it permits visualization of processes and their inter-relationships. Ground models should never be static but dynamic, with the ability to incorporate developments and adjustments from the refinement of earlier ideas in the light of more recent information. This leads from data, to knowledge, to understanding in a continuum that can be continually enhanced by successive iterations. The hydrocarbon industry is leading this approach, with the mineral exploration sector fast catching up and, in some cases, leading the way. The engineering sector, however, is lagging woefully behind. Unless it engages in more cross-sectoral technology transfers, it will be in danger of trying, expensively and unnecessarily, to re-invent the wheel of integrated data management.

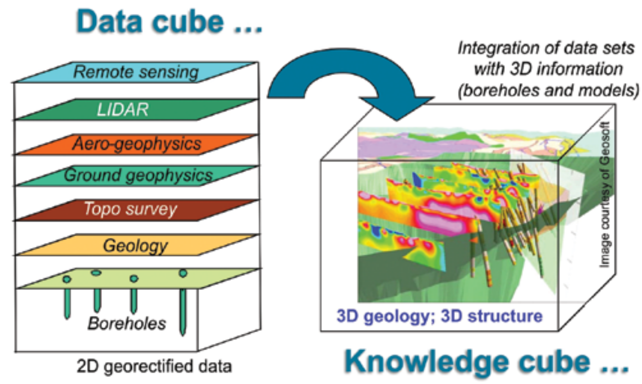

***Figure 4** Inter-relationship of components within a data cube leading to a 3D ground model continuum in a knowledge cube (Reynolds, 2008).*

Issues with interpretation

Eastwood (2011) recently stated that 'Seismic interpretation is not evolving fast enough to keep up with the phenomenal advances in acquisition, processing, and computing technology'. If this is true for the hydrocarbon industry, with the largest budgets and perhaps biggest risks, then it is also certainly true for other areas of geophysics, from mineral exploration through to environmental and engineering applications. The vast majority of near surface geophysical data is still acquired along 2D profiles and the corresponding 2D interpretation is at best interpolated into a 3D model.

With the increased ease with which geophysical equipment and software can be hired, geophysical data acquisition operations range from the highly experienced and professional through to the downright incompetent. Assuming that the data have been collected correctly (an assumption that is not always valid!), there can be a tendency to pump out colour maps without due thought as to what is being portrayed. The emphasis on speed of data acquisition coupled with the often unrealistic demands to produce reports within days of completing a field programme can lead to the use of default values in analytical software and production of maps without consideration of the accuracy and veracity of what is being reported. There is often a disproportionate emphasis on the collection of data rather than on the interpretation, where the acquisition of data becomes the end result rather than a means to a solution.

The near surface geophysics community is playing an increasingly important role in providing solutions to issues that affect modern society. With an ever increasing human global population, the demand for resources, and especially water and energy, requires far more efficient ways of managing our environment and the way we live. We therefore have a growing responsibility to ensure that the interpretations that are derived from geophysical data are as technically robust and as meaningful as possible, and that the results are as well communicated as possible. Herein lie a number of challenges for us all.

One of the common limitations evident almost across the board with geophysical interpretation is the lack of published relevant petrophysical properties of common materials, especially engineered or processed materials. For example, spectral induced polarization (SIP) interpretation is restricted by not having a publicly available set of diagnostic properties of a wide range of rock types of importance to the mining industry. Similarly, there are too few examples of SIP properties of contaminated soils or of contamination types to facilitate the application of this method to more environmental investigations. For GPR surveys, and particularly over modern engineered structures, interpretations are generally based on assumed values of dielectric constant for common materials rather than on measured values. There have been considerable developments in road pavement construction methods and materials but the interpretation of radar surveys is often hampered by the lack of up-to-date and relevant published dielectric properties of such materials.

Over the last few years, as a consequence of the drive for more renewable energy, there has been a massive increase in consideration of offshore wind farm developments around the UK coast among other areas. This has led to a huge demand for both hydrographic and sub-bottom profiling seismic reflection surveys. The wind farm developers have come to this arena from terrestrial wind farm developments and their approach has been predominantly engineering-led. This rapid upscaling of requirements has exposed large gaps in both physical capability and also the manner in which geophysical surveys are specified, executed and, in particular, interpreted. Out-of-date specifications have led to massive data sets being procured with little or no thought as to how the data would be processed, interpreted and subsequently managed.

Having been caught napping, some wind farm developers are turning to the oil industry to garner some of their experience. This is an appropriate response but is still a compromise. Oil industry geophysicists are not used to dealing with single-channel seismic data with a resolution of less than 0.5 m and have little experience in dealing with geotechnical engineers. The majority of interpretations of single-channel seismic data for wind farm developments use only a fraction of the information contained in these data sets. The geophysical contractors, perhaps more used to acquiring data for the hydrocarbon industry, have struggled to understand the requirements of the wind farm developers and vice versa, and for too long they have been talking past each other. Given the multi-billion pound development budgets and a growing realization of the potential risks in the offshore environment, some wind farm developers are starting to wise up and are beginning to recognize the need for a specific focus for wind farm industry geophysical interpretations. There are already examples of where hydrocarbon industry standard 2D/3D seismic interpretation packages are being used in conjunction with other high-level commercially available analytical software to produce 3D models incorporating both single-channel seismic data and borehole and CPT logs (Figure 5; for more details, see *Advances Wales*, issue 64, 2010). There needs to be specific expertise developed to manage, process, and interpret these data appropriately and to deliver suitable interpretations in terms of integrated 3D ground models in which borehole and CPT data are analysed in the same 3D volume as the seismic and hydrographic datasets. Furthermore, there is an increasing realization that there is far more to be gained from the seismic data than just interface elevations. One of the potential lines of research to be awakened by these issues is the development of multi-channel Boomer surveys, where the high-frequency content, and hence fine vertical resolution, is maintained while gaining the benefit of the additional data processing capability of multi-channel data, especially for velocity analysis.

For moderate to large and more complicated investigations, clients and their advisers may have specific requirements for types of information that they can use. This is increasingly the case in environmental and geotechnical investigations where more, and more complex, data sets need to be evaluated in some way or another. Sometimes this evaluation is limited by the end users not being aware of what information could be made available and therefore this constrains their own requirements according to their own understanding or perception of deliverables from geophysical surveys. As geophysicists we are good at communicating within our own circles but successive generations of geophysicists have been poor at explaining the benefits and limitations of geophysical techniques to non-geophysicists. Engineers commonly have high levels of scepticism about geophysics and are reluctant to use what they see as ‘black box’ technology with which they have little empathy. This has undoubtedly hampered the growth of environmental and engineering geophysics. It remains a significant challenge for engineering geophysicists but communication must be improved if greater acceptance of the geophysical tool box is to be achieved.

As an adjunct to what I have just written, another challenge in the geosciences generally is how to integrate

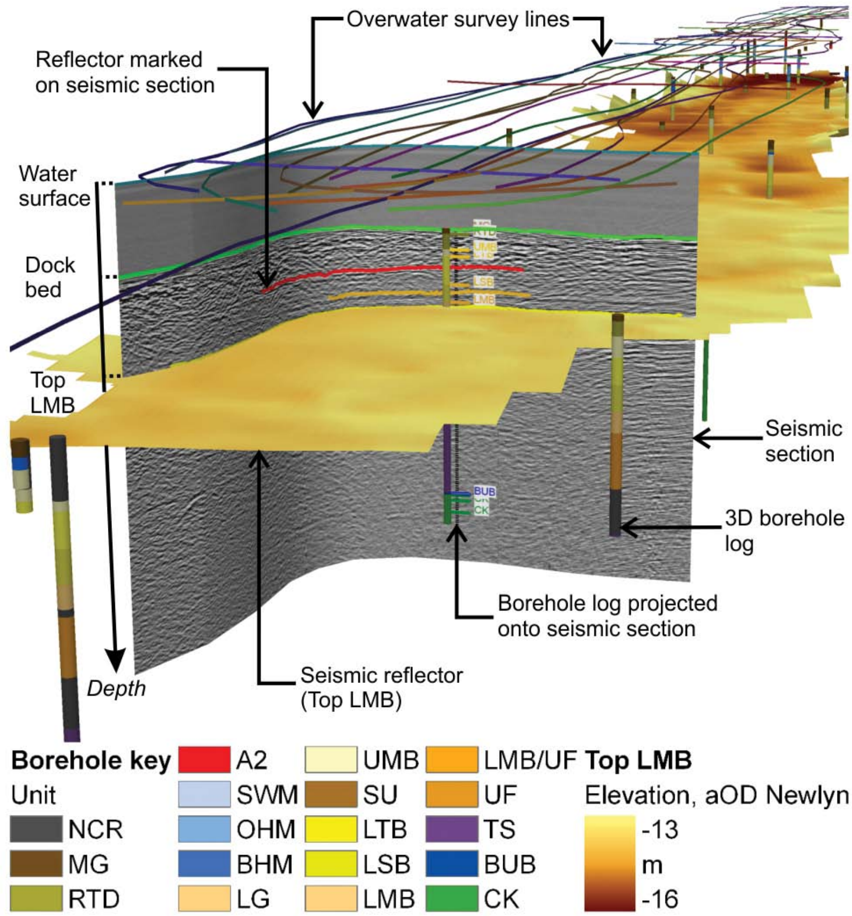

***Figure 5** Visualization of survey track plots, seabed bathymetry from multi-beam echo sounding, borehole data in AGS format and single-channel seismic data, and a sample interface interpreted from closely-spaced 2D Boomer seismic profiles.*

the various types of data into a single 3D ground model. Whereas historically, individual surveys, such as hydrographic, geophysical, geological, environmental, metocean, biological, etc., have been described in separate hard-copy reports, perhaps with a PDF version, their results have not been integrated through a central data management system accessible by different project team members remotely. Part of the difficulty of data integration is the variety of data formats, an issue with which the geophysical community is only too aware. However, engineering clients are beginning to recognize the need to be able to use geological and geotechnical information available in borehole and cone penetrometer testing (CPT) logs in conjunction with large hydrographic image mosaics of the seafloor, for example, along with the results of sub-bottom profiling seismic reflection interpretations. This is becoming an issue with the rapid growth in offshore wind farm developments around UK coastal waters and offshore Europe, where very large volumes of data are now being produced that need to be interpreted to produce outputs that can be used by different end-users, from geotechnical engineers, marine archaeologists, civil and structural engineers, through to project managers, and so on. This is where the offshore wind farm community and some parts of the mineral exploration sector would do well to learn from the experiences of the hydrocarbon industry, where this debate has been ongoing for some time but has yet to be resolved (e.g., Hawtin and Lecore, 2011).

The extension from the foregoing discussion is how to visualize the information once all the various data and their interpretations have been incorporated into a comprehensive data management system and the geological and geophysical results integrated into a 3D ground model. While the hydrocarbon industry has the benefit of visualization suites and associated technologies, this will remain out of contention for the wind farm industry and the near surface geophysics sectors for the foreseeable future. In the meantime, a continuing challenge for near surface geoscientists is how best to visualize the results, not only for the high-end technical users but also in communicating technical information to the wider public. This is where computer technology and graphics capabilities are coming to the fore in order to handle the increasingly large data sets. There is also increasing cross-talk with the medical imaging community so this represents a very exciting area in which we can expect some significant developments in the coming years.

Conclusions

One observation that has become clear from this brief overview is that many of the issues that are being faced by the hydrocarbon industry, albeit on a grand scale, also have to be tackled by the near surface geophysics community and colleagues within the associated geosciences. For example, reading Simms' (2011) personal perspective on rock physics, the same kinds of issues are prevalent within the geotechnical engineering geophysics arena. For too long, hydrocarbon exploration geophysics has been viewed within and without as being in a league of its own. Yet there is a growing need for greater dialogue between the hydrocarbon and near surface geophysics communities so that common challenges, although often at different scales, can benefit from the different perspectives.

There are significant gaps in our general understanding of the geophysical properties of geological and engineered materials that impede our interpretation. There are large areas for future research that, if successful, can significantly enhance the way that near surface geophysics is used for the wider benefit of society. As the demand for renewable energy drives the offshore survey market for near surface (<100 m bgl) surveys, the geoscientific community must be able to rise to the challenge of being able to provide robust and reliable 3D ground models that can be accessed by the wider wind farm user-base. Similar challenges exist within the mineral exploration market too, especially within junior mineral exploration companies.

As a near surface geophysical community we also need to become much better at communicating the benefits and limitations of geophysical techniques to a much broader user base, and training the next generation of geophysicists to carry the mantle forward. These are undoubtedly very exciting times to be involved in the near geophysics sector and, if the next 15 years lead to as many new developments as the last, I can't wait to see what the future holds.

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