The geological Hubble: A reappraisal for shallow water

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Traditional two-dimensional (2D) seismic acquisition techniques image the subsurface using a grid of orthogonal lines. Dips are recorded only in the along-track direction, limiting migration to a 2D along-track approximation of the inherently 3D wavefields. This produces profiles that are often complicated by out-of-plane reflections and with resolution (for structural interpretation) constrained by the line spacing rather than the source wavelength. The acquisition of true 3D seismic reflection data, in contrast, provides dip information for the reflected wavefields in both along- and across-track directions. This allows a full treatment of the 3D wavefields during migration, affording accurate 3D structural reconstruction, significantly improved resolution (theoretically 1/2 source wavelength), and increasing signal-to-noise ratio (SNR) through more effective noise cancellation.

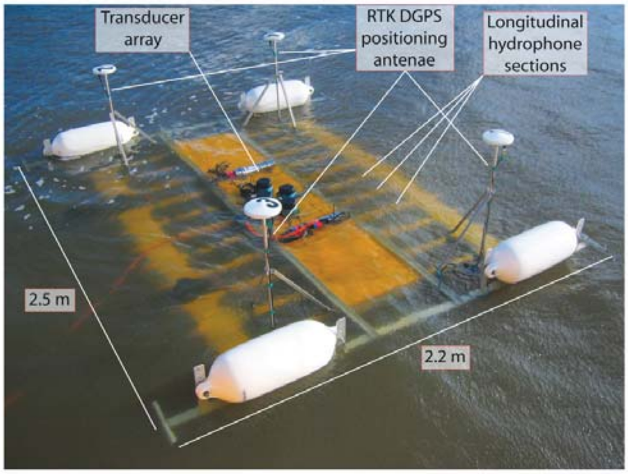

Figure 1. *Annotated photo of 3D chirp sub-bottom profiler.*

The advances in basin-scale research permitted by these techniques, led Cartwright and Huuse (2005) to describe 3D seismic technology as "the geological Hubble." The ability to accurately image features over large areas has dramatically improved our understanding of geological systems at the basin-scale. Research areas as varied as fault linkage and growth, fluid-rock interactions, paleo- land- and seascape mapping using submarine channels and fan systems, and mass transport of sediment between shallow and deep waters have all benefitted. In addition, the order of magnitude improvement in horizontal resolution has allowed a range of discrete structures, such as impact craters and volcanic intrusions, to be interpreted and mapped.

Transferring these techniques into the shallow-water environment has important implications for advancing our understanding of the morphodynamics of the Earth. Numerous structures are observed on scales spanning several orders of magnitude (10s m to km) and in a range of water depths (< 100 m to km). Mass transport deposits, for example, are commonly imaged both as continental margin events involving > 1000 km^3 of material (e.g., Storegga slides, offshore Norway), and as < 0.001 km^3 of material in fjords and lakes (e.g., Finneidfjord or Trondheim, Norway). Similarly, polygonal fault systems, which play an important role in controlling fluid flow in major basins, are theoretically predicted to occur in multiple phases. The smaller systems that operate on the meter-to-decameter scale remain poorly understood, having been imaged only by coarse grids of 2D profiles.

Shallow-water application

Basin-scale surveys use receiver separations of 10–100 m and source array bandwidths of 50–100 Hz. According to basic sampling theory, accurate sampling of the reflected wavefields such that energy from multiple sources and receivers can be coherently summed during migration, requires that each source/receiver pair be absolutely positioned in x, y, and z to better than 1/4 the source wavelength. This requirement equates to positioning accuracies of a few meters.

In order to acquire shallow-water, decimeter-resolution 3D seismic volumes, the two most common seismic sources are boomer and chirp sub-bottom profilers. Typical frequency ranges of 0.4–4.0 kHz and 1.0–24.0 kHz, respectively, equate to a required absolute positioning accuracy of 1.0–2.0 cm in x, y, and z. This presents a significantly greater technological challenge than traditional 3D seismic positioning requirements, which are easily attainable using modern differential GPS systems. For near-shore applications (where a local base station can be installed), real time kinematic (RTK) GPS positioning systems offer an effective solution. However, these systems are range-limited by the accuracy of the atmospheric corrections, and may require a post-processing kinematic (PPK) approach to obtain the required accuracies when operated several 10s km offshore.

Considerations for positioning at this scale are also fundamentally linked to the survey design. If a source and parallel streamer array similar to standard industry techniques is used, relative fluctuations in the source/receiver positions caused by wave motion and/or boat wake will also cause problems. Although such submeter-scale variations would be undetectable in larger 3D data sets, they are significant for decimeter-resolution seismic surveys (Bull et al., 2005; Missiaen, 2005). By fixing the source/receiver geometry onto a rigid frame, these relative fluctuations can be removed, being replaced by pitching and rolling of the whole array. Attitude (heading, pitch, and roll) data as well as RTK–GPS positions will accurately describe this motion, allowing each source-receiver pair to be positioned through a matrix transformation of the

Source	No. receivers	Bin size	Sampling interval	Positioning accuracy	Pulse rate
4 Chirp transducers (1.5–13.0 kHz)	60 (25.0 cm spacing)	12.5 cm	0.02 ms	X= ±0.46 cm Y= ±0.70 cm Z= ±1.82 cm	4–8 s^{-1}

Table 1. *Summary of 3D chirp sub-bottom profiler.*

RTK–GPS antenna location (Bull et al., 2005).

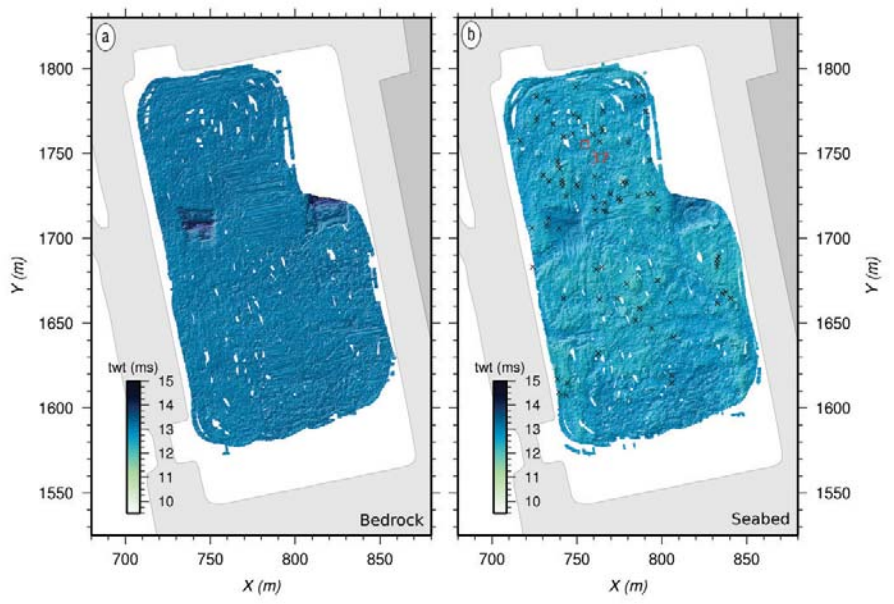

Figure 2. *Bedrock (a) and seabed (b) surfaces. Both use the same color palette. Seabed surface is overlain by black crosses indicating the buried object locations. Target 37 shown in Figure 3 is labeled in red. Figure adjusted from Vardy et al. (2008).*

Case studies

To illustrate the effect/impact of acquiring true 3D seismic data in shallow water, three case studies are considered. These data were acquired using the 3D chirp sub-bottom profiler (developed jointly by the University of Southampton and GeoAcoustics), which uses a polycarbonate frame to fix the array of 60 hydrophones around a central chirp source (Figure 1 and Table 1). By combining RTK navigation and attitude data, each source-receiver pair is positioned in real time to an accuracy of: x = ± 0.46 cm; y = ± 0.70 cm; z = ± 1.88 cm. This allows traces to be appropriately binned onto a 12.5 x 12.5-cm (half the 25-cm receiver spacing) common midpoint (CMP) grid, while the broadband, high-frequency chirp source (linearly sweeping between 1.5 and 13.0 kHz) waveform provides the potential for decimetric vertical resolution.

Starting with small-scale discrete targets and moving to larger, local-scale geological structures, we consider case studies that span engineering, archaeological, and geological applications.

Case study 1: Engineering and homeland defense. Decimeter-scale imaging of the seabed and subseabed is a fundamental part of marine engineering and homeland defense applications. Traditionally, shallow site surveys to map small-scale geological changes, discrete objects, and/or infrastructure integrity use a combination of surface-scanning acoustics (e.g., swath bathymetry or side-scan sonar), a sparse (> 10 m) grid of 2D seismic profiles, and divers. While significant recent advances have been made in remotely identifying and monitoring seabed structures using high-frequency surface-scanning acoustics, the limited effective resolution of 2D seismic profiles has restricted applications in the subsurface.

To illustrate the effectiveness of acquiring a true 3D seismic volume we consider a case study from an atidal basin on the south coast of England (Vardy et al., 2008). The 150 x 200-m study area was surveyed using the 3D chirp sub-bottom profiler to map localized bedrock protrusions and the distribution of discrete buried objects. In two days, more than 20 million traces were acquired, providing 95% ground coverage, and an average fold of 15 traces per 12.5 x 12.5-cm CMP bin. Using a combination of CMP stacked and prestack Kirchhoff-migrated volumes, 3D morphology of the Devonian slate bedrock, a thin veneer of overlying unconsolidated, fine-grained sediments, and 89 individual acoustic anomalies were interpreted (Figure 2).

While no bedrock protrusions were found (only two depressions), the large number and distribution of acoustic anomalies identified in the 3D seismic volume resulted in a comprehensive site clearance program, which involved systematic dredging of the entire site and demonstrated a 100% success rate in locating all discrete buried objects. This afforded a direct comparison of the interpreted acoustic anomalies with coincident recovered objects. For example, Figure 3 illustrates this comparison for acoustic anomaly 37, a 1.8-m, polarity reversed, high-amplitude reflection sitting 0.25 ms (approximately 0.18 m) above the bedrock surface (Figure 3c). In the horizon slice through the peak of the Klauder wavelet (Figure 3a), it can be seen to widen sharply at the southern end, from 0.5 to 1.0 m. This reflector morphology agrees exceptionally well with the coincident object, a heavily degraded wooden pole 0.10 x 0.13 x 1.80 m in dimensions with a U-shaped metal plate bolted on to one end (Figure 3d). In addition to the striking correlation in morphologies, the reverse-polarity reflection also agrees with the heavily degraded and, presumably, waterlogged nature of the recovered object.

Although one has to be careful regarding reflector ampli-

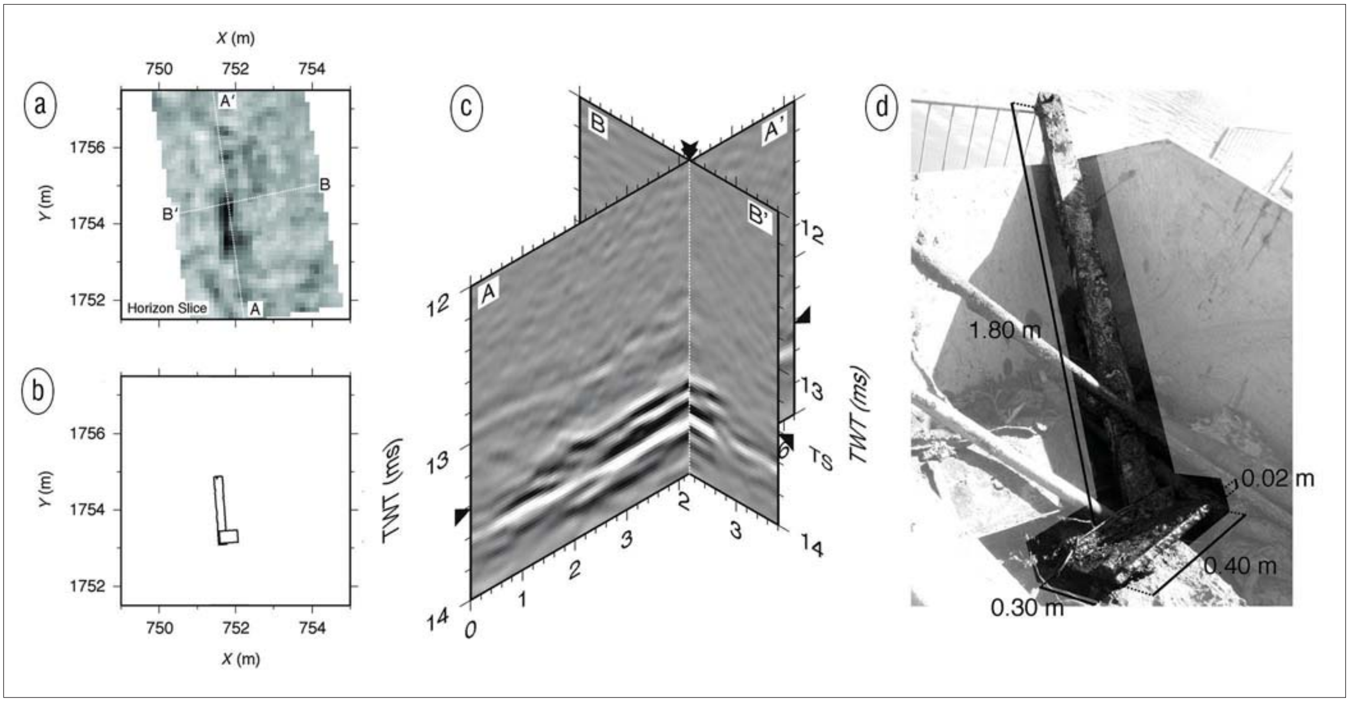

Figure 3. *Horizon slice (a), interpreted object (b), and fence diagram of along-object-axis and across-object-axis vertical profiles through a prestack Kirchhoff-migrated volume centered on acoustic anomaly 37 (c). Panel (d) is a photo of the coincident dredged object, from which the scale drawing in (b) was made. Vertical exaggeration of A–A' and B–B' profiles in fence diagram is 4:1. Figure enhanced online.*

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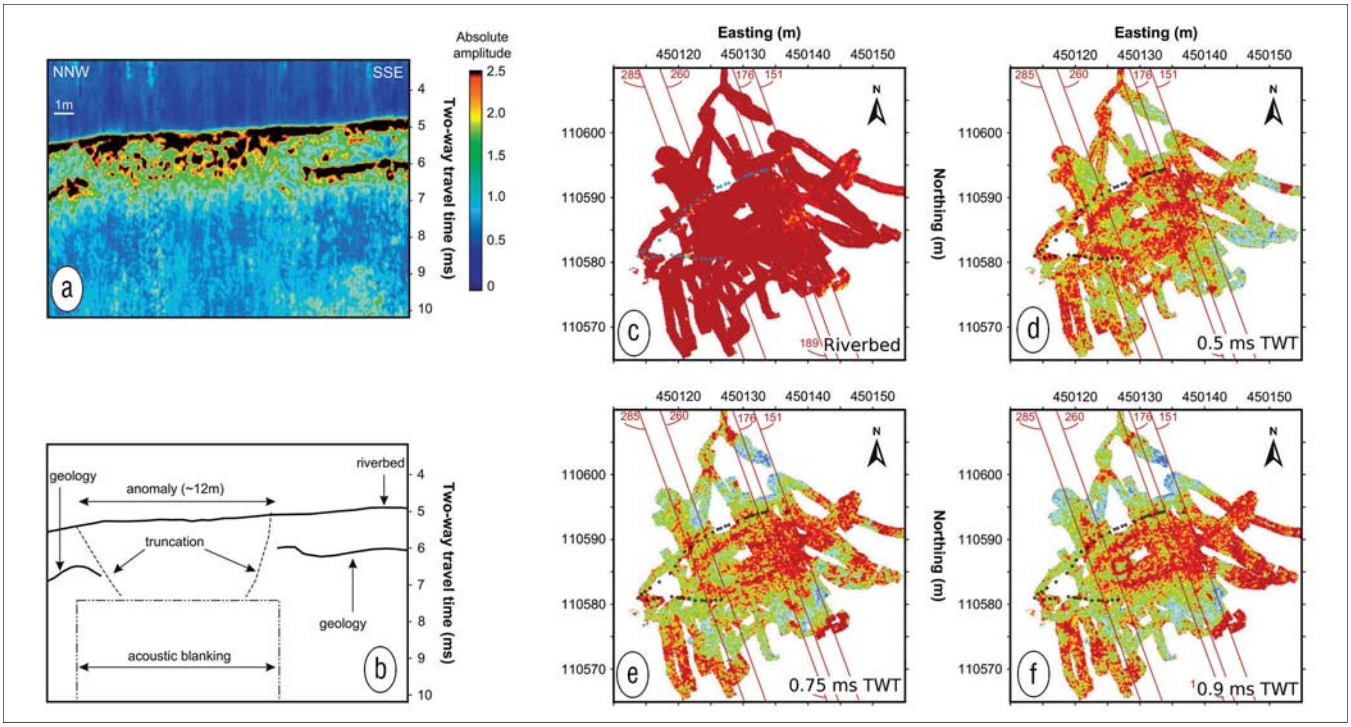

Figure 4. *Vertical profile (a), interpreted section (b), and time slices, (c)–(f) from 3D seismic volume over the* Grace Dieu *wreck site. Time slices are at the riverbed (c) and depths of 0.5 ms TWT, 0.75 ms TWT, and 0.9 ms TWT, respectively. Note the rectangular feature within the hull on the 0.9-ms time slice. Dots indicate GPS surveyed positions of exposed timbers. Vertical exaggeration of 2:1 used on profiles. Figure adjusted from Plets et al. (2009).*

tudes when the target objects are nearing seismic wavelengths in size, these data have demonstrated the ability for discrete object detection using decimeter-resolution 3D seismic techniques. On average, the objects had dimensions of 1–2 m, meaning that, to produce a comparable level of successful identification, 2D profiles would have to have been acquired on a grid with line spacing of 1–2 m (similar to the 1.25-m swath width of the 3D chirp sub-bottom profiler). Even in this case, the lack of across-track dips would make positioning each object (only really possible post-migration) limited to about 1–2 m accuracy, and 2D data would never afford a comparable assessment of object size and shape to that obtained using the 3D data set. With the extra knowledge obtained from the 3D volume, it was possible to predict object locations for each individual dredge grab (note, a 0.66 m^3 bucket dredge was used), permitting extremely rapid, targeted dredging.

Case study 2: Marine archaeology. Marine archaeological investigations are time-consuming and difficult. Classically they consist of a series of diver excavations that attempt to copy (as closely as possible) the rigor and attention to detail practiced by their terrestrial counterparts. However, divers are limited greatly by environmental conditions such as water temperature, site depth, currents, tides, and visibility. The act of unearthing the archaeological remains is also contentious, with a large number of sites demonstrating significantly increased degradation after they have been exposed to seabottom conditions.

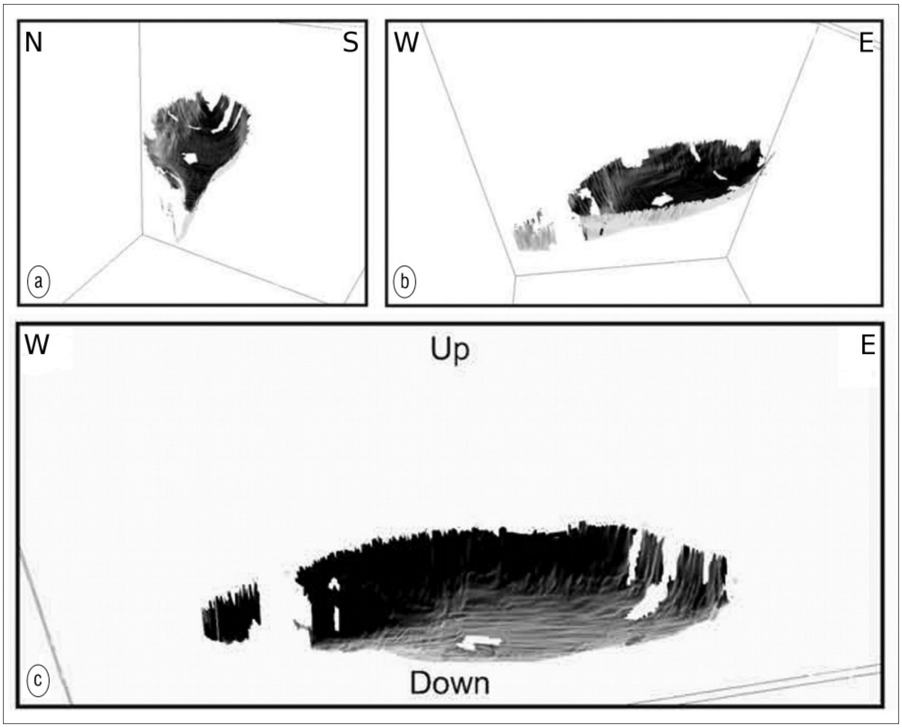

Figure 5. 3D reconstruction of the buried remains of the Grace Dieu. *Vertical exaggeration 2:1. Image modified from Plets et al. (2009). Figure enhanced online.* [URL: http://dx.doi.org/10.1190/1.3555325.2]

As a result, high-resolution marine geophysical techniques (such as swath bathymetry, side-scan sonar, and chirp/boomer sub-bottom profilers) are increasingly being used to remotely map marine archaeological sites (a trend that is also becoming increasing popular for terrestrial locations). These approaches have the advantages of being nonintrusive and rapidly cover large areas of seafloor, but suffer from the same limitations as shallow engineering surveys—namely the limited resolution potential afforded by 2D seismic surveys.

The wreck of Henry V's flagship, the *Grace Dieu*, in the Hamble River, Southampton, was surveyed over two days using the 3D chirp sub-bottom profiler (Plets et al., 2009). The strong tidal conditions and shallow-water (< 4 m) limited surveying to an hour either side of slack water each day. During these four hours of surveying, more than 100,000 traces were acquired in the 30 × 30-m survey area, providing 85% ground coverage and an average CMP fold of 20.

The archaeological remains were observed as a high-amplitude anomaly that truncated surrounding bedrock reflectors and acoustically blanked all underlying structure (Figures 4a and 4b). In time slices through the 3D volume, the anomaly appeared ovate, and diminished in size with increasing depth (Figures 4c to 4f). Comparison of this feature with RTK–GPS mapping of timbers exposed at low tide confirmed that this high-amplitude anomaly corresponded to the hull of the *Grace Dieu*. Interpretation of this anomaly throughout the 3D volume allowed a 3D reconstruction of the archaeological remains without an expensive, time-consuming, and potentially damaging excavation (Figure 5), indicating, among other things, that the hull has hogged (i.e., the keel has raised in the midship section and sagged at the bow and stern). These data allowed a full reconstruction of the hull of the *Grace Dieu*, including extension above the preserved timbers using prior knowledge of medieval shipbuilding techniques, producing a reconstructed hull that closely resembled those described in historical literature. In addition, a large, coherent rectangular feature 2 m in length was identified within the chaotic internal reflectors of the wreck site, which may correspond to the mast step.

While, at present, 3D sub-bottom profiler surveys of buried marine archaeological structures do not achieve the same accuracy and resolution of hand excavations, the speed and ease with which complex buried structures can be mapped is extraordinarily useful. While a prior 2D chirp survey had largely mapped a similar hull reconstruction, details like the hogged hull and mast step had not previously been identified. Sites such as the *Grace Dieu*, which is a small archaeological site, would require dedicated diver excavations over several years to produce enough data for the same kind of hull reconstruction (probably at the expense of critically degrading the wreck site) that the marine geophysical techniques achieved in just two days on site. The results of this survey can be used to better target ongoing and future dive time, filling in details that were not resolved by the acoustic imagery.

Case study 3: Geological applications. In much the same manner as basin-scale geological structures, local-scale geological problems have a complex 3D nature that cannot be adequately described using a coarse grid of 2D seismic lines. Geological structures on the 10s- to 100s-m scale are

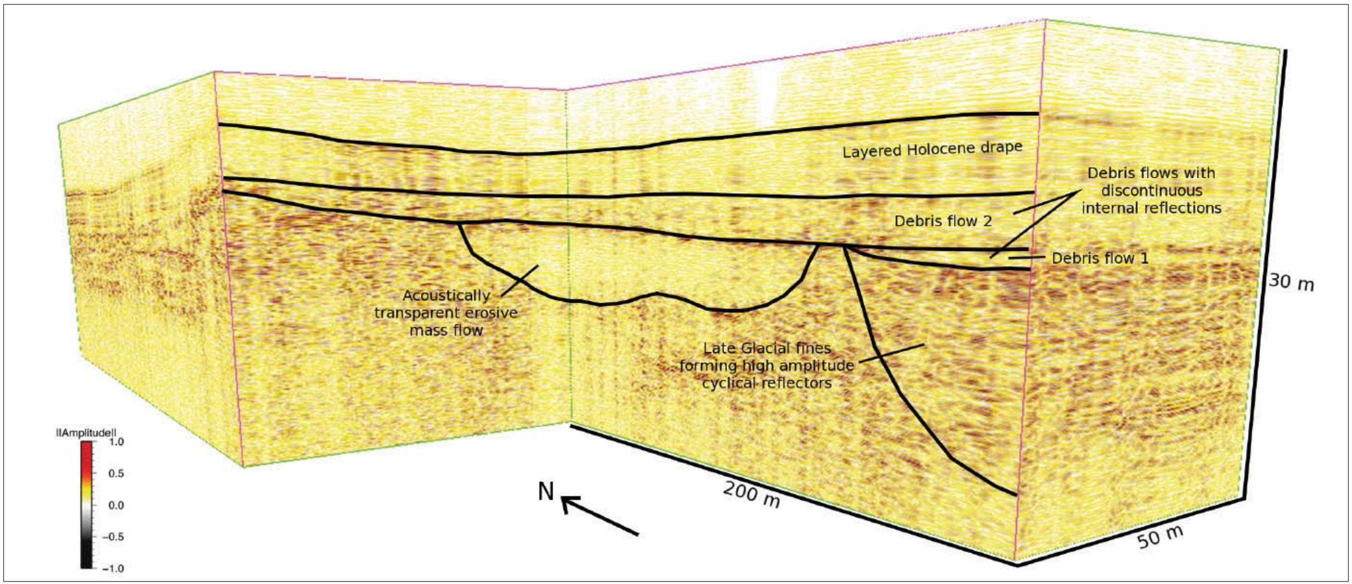

Figure 6. *Cutaway voxel volume over buried Younger Dryas mass transport deposits. Attributes of two debris flows and erosive mass flow are labeled. Vertical exageration 5:1.*

extremely poorly preserved in the terrestrial environment. Weathering and erosion, along with anthropogenic activity, quickly limit their scientific value. This makes obtaining high quality marine imagery of geological features on this scale extremely important. Decimeter-scale 3D seismic imaging allows detailed geomorphological mapping of structures such as buried drainage patterns, shallow gas migration pathways, sea level change features, sediment mobilization/scour, and glacial landforms.

On the continental shelf, 3D seismic imaging of mass transport complexes is particularly effective, bridging the gap between localized core stratigraphy and regional 2D seismic profiles, thereby allowing the complex three-dimensional nature of these features to be investigated. Here we consider a shallow-water lacustrine case study in Windermere, United Kingdom, where buried mass movement deposits of Younger Dryas age (12.9–11.7 ka before present) are imaged using the 3D chirp sub-bottom profiler (Vardy et al., 2010). The 100 x 400-m area was surveyed over three days, resulting in more than 12 million traces providing 83% ground coverage. Due to slightly low SNR, traces are binned onto a 25 × 25-cm CMP grid, raising the average CMP trace fold to 14.

What was originally interpreted as a single erosive mass flow using regional 2D seismic data can be resolved using the 3D seismic volume into three distinct deposits (Figure 6). Combining package morphologies with seismic attributes enabled these three deposits to be classified as: a small (about 1500 m^3) debris flow containing several deformed translated blocks and propagating in a easterly direction; a large (about 500,000 m^3) homogeneous, fine-grained erosive mass flow that propagated in an northeasterly direction, incising up to 4 m into the pre-existing sediments; and a smaller (about 60,000 m^3) southeasterly propagating debris flow with numerous small (up to 2.0 × 8.0 m) deformed translated blocks (Figure 7). Using these observations, it is possible to discern two distinct deposition mechanisms within the lake: small-scale heterogeneous debris flow deposition, possibly of terrestrial origin; and the larger submarine failure of fine-grained material due to slope overloading around the end of the Younger Dryas climatic event.

Pre-existing 2D seismic profiles allow identification of a single, large (about 500,000 m^3) erosive mass flow deposit. However, little information regarding the total volume, deposition process, and direction of flow can be obtained. The acquisition of a decimeter-resolution 3D seismic volume over the site enables the identification of the further, smaller mass transport deposits—both debris flows. Detailed 3D mapping of package morphologies and seismic structure allows estimates of deposit volumes, directions of propagation, and possible deposition mechanisms.

Conclusions

We have shown that combining a high-frequency sub-bottom profiler source with a solid array of closely spaced (25 cm) hydrophone groups enables the acquisition of coherent decimeter-resolution true 3D seismic volumes. These surveys afford complete imaging of small-scale (10s to 100s m) geological, engineering, and archaeological targets, from which structural morphologies can be mapped in three dimensions at decimeter resolution. A major limiting factor for present shallow-water 3D seismic acquisition, particularly for geological applications, is the small footprint size. The 3D chip sub-bottom profiler is 2.5 m wide with a central source array, which equates to a footprint width of 1.25 m. Therefore, to acquire 100% ground coverage and achieve suitable data redundancy a sail-line spacing of 1.0 m is required. While it has been demonstrated that prestack Kirchhoff migration can adequately recover small (< 1 Fresnel zone) gaps in coverage if SNR is good (e.g., Vardy et al., 2008 and 2010), the maximum areas that can be covered within a "normal" shallow-water survey are generally limited relative to the size of most shallow-water geological structures. The largest single

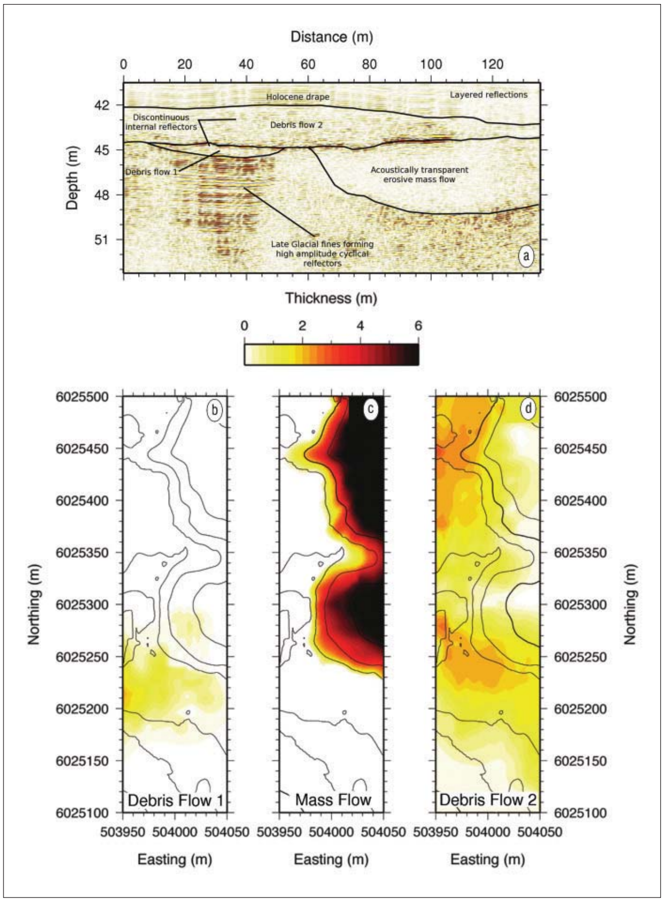

Figure 7. *Vertical profile through 3D seismic volume (a), along with isopach maps for three mass transport deposits, superimposed on basal contours (b). Attributes of the two debris flows and erosive mass flow are labeled. Vertical exaggeration 5:3.*

area surveyed to date being 200 x 1100 m in four days.

In Windermere and similar data sets, we used pre-existing 2D seismic profiles to target smaller areas of increased complexity where a 3D seismic volume would be most significant. This approach is exactly the same as was used before basin-scale 3D seismic acquisition became commonplace 10–15 years ago. With advancing technology, constant refinement of acquisition techniques, and a rapidly increasing interest in shallow-water 3D seismic applications, the size of volumes being acquired is consistently growing. In the three years since the engineering example was acquired, volume sizes have increased from 30,000 m^2 to 220,000 m^2 (i.e., a factor of seven). Similar continued growth can only improve our ability for coherent, high-resolution geomorphological mapping of large (100s m) shallow-water geological, archaeological, and engineering targets.

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Acknowledgments: The authors thank the Engineering and Physical Sciences Research Council/Joint Grant Scheme (GR/R 12695/01) and GeoAcoustics Ltd. for their help in developing the 3D chirp sub-bottom profiler and the UK Ministry of Defense (SAMO), English Heritage, and the Freshwater Biological Association for their help in acquiring the three case study data sets.

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