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Bicentennial Review

The impact of 3D seismic data on the understanding of compaction, fluid flow and diagenesis in sedimentary basins

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Abstract: Three-dimensional seismic reflection surveying is one of the most exciting technology-driven developments in the Earth Sciences over the past century. Three-dimensional seismic data present the geoscience community with an extraordinary ability to map structures and stratigraphic features in 3D detail to a resolution of a few metres over thousands of square kilometres. This resolving power has been a major factor in the recent recognition of a number of previously unsuspected phenomena in sedimentary basins and has led to some significant insights in basin analysis. This paper reviews some of the recent advances in basin analysis made using the medium of 3D seismic data, focusing on the broad field of fluid–rock interactions in sedimentary basins. Several recently discovered phenomena are reviewed, including polygonal fault systems and large-scale fluid flow pipes. Three-dimensional seismic data have also been invaluable in documenting the spatial variability of diagenetic fronts. The potential for future developments in this field of geophysical interpretation is considerable, and a number of potential areas for future research are highlighted.

In many geological disciplines significant advances have often been made as a result of the introduction of new technology. The archetype of this technology stimulus must surely be the role of seaborne acquisition of magnetic data from the ocean floor and its impact on our understanding of plate tectonics. In basin analysis, the single technology that has exerted the greatest impact over the past few decades is undoubtedly seismic reflection profiling.

Seismic reflection profiling has its origins in the 1920s, and only developed slowly during the 1930s to 1950s. The coming of the digital age transformed the acquisition and processing of seismic data, and improvements in the quality of 2D seismic reflection profiles were rapid through the 1970s and early 1980s, to the point where the 2D seismic method exerted a major influence on the development of basin analysis as a discipline. The publication of the landmark AAPG Memoir 26 on seismic stratigraphic interpretation (Payton 1977), for example, offered a systematic new approach to the seismic interpretation of sedimentary sequences and transformed the way in which stratigraphy could be used to unravel basin evolution in the broadest sense.

A major advance in the seismic reflection method came in the early 1980s with the advent of 3D seismic surveying (Sheriff & Geldart 1995). The main problems of limited spatial resolution of the 2D seismic method were solved by acquiring such dense survey grids that new processing methods could be introduced, and these in turn improved imaging quality dramatically (Nestvold 1996; Dorn 1998). The typical 3D seismic survey is acquired with a line spacing of 25 m or less, and this results in very dense subsurface sampling, which automatically enhances spatial resolution (Hart 1999). It is this improvement in spatial resolution that has provided the main advance from a research perspective, as subtler details of structure or stratigraphy can now be observed. Many features that were too small to be seen at all using the relatively coarse 2D seismic grids with line spacings of a few kilometres have now been brought into focus. In addition to the improvements of spatial resolution, the late 1980s and 1990s have seen advances in processing methods designed specifically for 3D data, and these have led to enhanced vertical resolution and spatial imaging (Yilmaz 2001).

The impact of the early 3D seismic surveys was to some extent limited by their small areal extent (typically $<100\ km^2$), mainly because of the high costs of dense 3D surveys, and hence tended to be located in small areas above producing fields. These early surveys were therefore only of limited value to the wider basin research community and their impact was primarily within the development and production of hydrocarbon resources (Weimer & Davis 1996). Nevertheless, important research advances were made with these early generation 3D seismic surveys, particularly within the fields of reservoir geophysics and structural geology (e.g. Bouvier *et al*. 1989; Nestvold 1996).

Technological innovation in the past decade has resulted in survey areas growing in size by an order of magnitude or more, to the point where individual surveys are now acquired over areas of $>10\,000\ km^2$. Over this period, computer-based interpretation and visualization technology has improved dramatically to the point where the interpreter can track horizons and faults and calculate seismic attributes for data volumes in the tens or hundreds of Gigabytes. These large 3D seismic surveys are now almost of truly basinal extent, allowing basin-scale geodynamics to be investigated along with a much more holistic treatment of deformational and depositional processes. In the North Sea Basin, for example, there is almost continuous 3D seismic coverage over an area exceeding $100\,000\ km^2$. When combined with extensive bio- and lithostratigraphic constraints from boreholes, this availability of data gives basin analysis a fundamentally novel tool. With this tool, we now have the potential to address regional tectonics, depositional systems and processes, igneous systems, fluid flow, compaction and even diagenesis in a truly 3D context.

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The main aim of this paper is to review the impact that 3D seismic surveying has made as a research medium in the general thematic realm of fluid–rock interactions in sedimentary basins. Recent reviews of the broader use of 3D seismic data across the spectrum of basin analytical themes and related disciplines have shown the great potential that exists in applying this technology to geological research (Davies *et al*. 2004; Cartwright & Huuse 2005; Davies & Posamentier 2005). Research into fluid–rock interactions in sedimentary basins is a broad theme that has to date been based mainly on outcrop studies or scientific drilling (Maltman 1994). The coupling between fluids and rock deformation is widely appreciated as a critical linkage with implications for the mode of deformation and for the flow of fluids in the crust. Three-dimensional seismic data are now beginning to make an impact on this field of research by providing evidence of direct interactions in three dimensions, thus defining the structural controls on fluid plumbing in the upper crust (e.g. Heggland 1997, 2004; Hurst *et al*. 2003; Huuse & Cartwright 2004; Ligtenberg 2005). The intention here is not to provide an exhaustive review of this broad theme, but to provide some research highlights of insights that have derived from the use of 3D seismic data that give a sufficiently broad summary of past achievements to demonstrate the wide-ranging potential of the method, as well as the enormous potential of the ultimately researchable database. The examples presented below are grouped into three main themes: polygonal fault systems, focused fluid flow pathways, and diagenesis.

Polygonal fault systems

Polygonal fault systems are laterally extensive arrays of extensional faults that are confined to a specific stratigraphic interval (i.e. they are layer-bound). They were first described using 3D seismic surveys, and are thus an excellent example of a relatively recent geological discovery made exclusively through this medium. Polygonal fault systems are widely developed in many continental margin basins, abyssal basins, and some foreland and intracratonic basins (Cartwright & Dewhurst 1998). Individual polygonal fault systems are often developed over areas in excess of 100 000 km^2, and in a few cases over a million km^2. The stratigraphic units in which the faults are concentrated are generally very fine grained and commonly comprise smectite-rich claystones or biogenic mudstones (Cartwright & Dewhurst 1998; Dewhurst *et al*. 1999), but in some cases relatively thick sandstone units can also be deformed by the polygonal faults, particularly when they are interbedded with thicker intervals of fine-grained strata, as in the case of the Ormen Lange reservoir (Stuevold *et al*. 2003).

Individual faults making up the arrays generally have small throws (<100 m), and propagate with a diverse range of strikes such that the array has a polygonal appearance in planform (Fig. 1). This polygonality of the array is the defining characteristic of the system as a whole, and is one of the main lines of evidence leading to the view that polygonal fault systems are not formed as a result of regional tectonic stresses. The polygonal planform geometry is generally developed at a scale of 500–1000 m; that is, the typical closed polygon or near-closed polygon has a cell dimension in this range. This scale limit means that the essential characteristic of polygonality can only really be mapped seismically using a grid with a line spacing of <100 m, and more ideally, <50 m. For a typical 2D seismic reflection survey with a grid spacing of >500 m, the fault pattern could not be constrained because the fault intersections with the profiles would be spatially aliased (see Freeman *et al*. 1990, for discussion of spatial aliasing of fault patterns).

3D seismic interpretation of polygonal fault systems

The problem of spatial aliasing applied to the identification of polygonal fault patterns serves as an excellent illustration of how the improved spatial resolving power of the 3D seismic method can lead to the identification of previously unrecognized geologi-

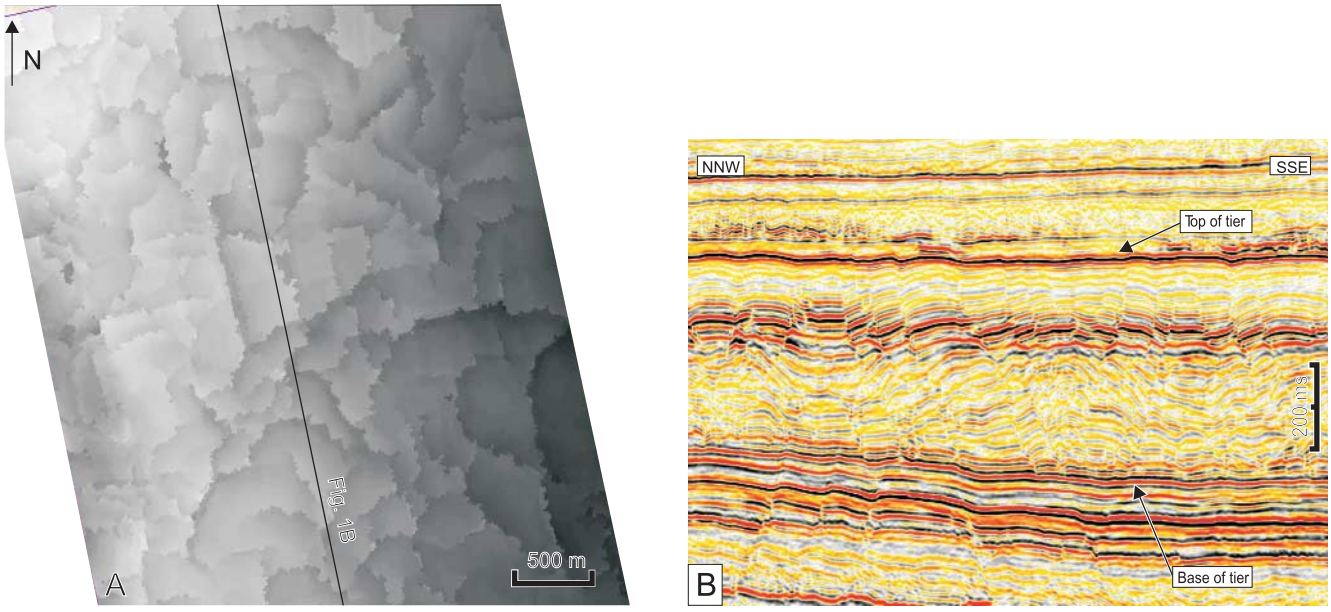

Fig. 1. Planform and cross-sectional characteristics of polygonal fault systems. (**a**) Structure map in two-way travel time of part of a polygonal fault system deforming Neogene biosiliceous mudstones offshore Norway, showing the typical planform of the fault network. (**b**) Part of a seismic profile across the map in (**a**), showing the layer-bound nature of the faulting, with upper and lower boundaries of the faulted 'tier' clearly shown following stratigraphy.

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cal phenomena. To demonstrate this further, let us consider the fault intersection nodes depicted in Figure 2. A polygonal fault system has been mapped from a 3D seismic survey with a line spacing of 25 m (Fig. 2a). It has then been subsampled at 250 m and 1000 m line spacing in one direction, with a coarser line spacing of 500 m and 1000 m, respectively, in the orthogonal crossline or strike direction (Fig. 2b and c). It is just about possible to connect the fault intersection nodes in the case of the 250 m by 1000 m subsample (Fig. 2b), and to obtain a fault map with a reasonable degree of correlation with the map made at 25 m line spacing, but the same task is too unconstrained to give any meaningful result for the 1000 m by 1000 m line spacing. This simple example thus demonstrates the critical role of line spacing in avoiding spatial aliasing as discussed by Freeman *et al*. (1990), and applies more generally to a wide range of geological objects. It also shows the impracticability of recognizing a typical polygonal fault pattern using standard grid dimensions of either industry or research 2D seismic surveys.

The example presented in Figure 2 provides a simple explanation of why such a widespread geological phenomenon could have remained undetected for so long, and was only identified once the first 3D seismic surveys were acquired over areas affected by this type of faulting. Indeed, numerous reports of small extensional faults confined to specific stratigraphic intervals were made in the 1980s and early 1990s (Henriet *et al*. 1989; Verschuren 1992) and these were rightly attributed to non-tectonic mechanisms such as differential compaction, overpressure, dewatering, and density inversion, anticipating the conclusions of future research studies that were to be based on 3D seismic data in the 1990s. 2D seismic data were able to show the stratigraphic confinement of these fault systems, and on the better quality profiles were also able to give a reasonable image of the throw distribution of these faults. However, because of their intrinsic property of strike variation, any 2D profile by necessity crossed a set of faults at a range of obliquities with true dip sections interspersed with oblique and strike fault plane sections. As a result, 2D migrations often result in poor imaging of the fault planes, and their true geometry is difficult to fully appreciate. The geometrical challenge presented by polygonal faults to imaging by seismic reflection surveys can be addressed by full 3D seismic migration, where dip panels in varying strike directions can be correctly migrated into their true spatial position (Yilmaz 2001; Brown 2003). The typical contrast in quality of imaging between the 2D as opposed to a full 3D seismic migration is illustrated by comparing a 2D and 3D reflection profile along the same transect through a polygonal fault system (Fig. 3). This comparison shows the problems likely to be faced when attempting a structural interpretation of polygonal faults using 2D seismic data.

The improvements in 3D seismic acquisition and processing that have taken place in the past decade or so have been mirrored by improvements in the capabilities of computer-based interpretation techniques, and these have had a major impact on the interpretation of polygonal fault systems. Initially the interpretation of polygonal fault systems was based on horizon mapping using a closely spaced grid from a given 3D survey, using the line density to correctly define the fault pattern by connecting hanging-wall and footwall cutoffs (Cartwright 1994). One other crucial advantage offered by the 3D seismic method could also be exploited. The high spatial sampling of the subsurface in a 3D survey means that a cube of data is available for manipulation, and profiles with arbitrary strike and dip can be extracted from the data volume. Initially, interpretation methods focused on the extraction of horizontal (time) slices from the volume, and these formed a useful complementary approach to simple profile interpretation (Brown 2003). Time slices through polygonally faulted intervals exhibit a specific pattern, and on the better resolution data it was possible to trace the polygonal planform of the polygonal fault systems, because fault planes could be identified from abrupt terminations of stratal reflections (Fig. 4). There are significant difficulties in making structural interpretations from time slices alone, however, mainly because of the effects of slicing horizontally across gently inclined stratal reflections.

In the mid- to late 1990s, various advanced processing methods were developed to enhance the volumetric approach to interpretation. Most important of these was the technique to extract the coherence of the data volume (also known as semblance or variance), or the degree of lateral continuity of reflections (Bahorich & Farmer 1995). This method was tailored

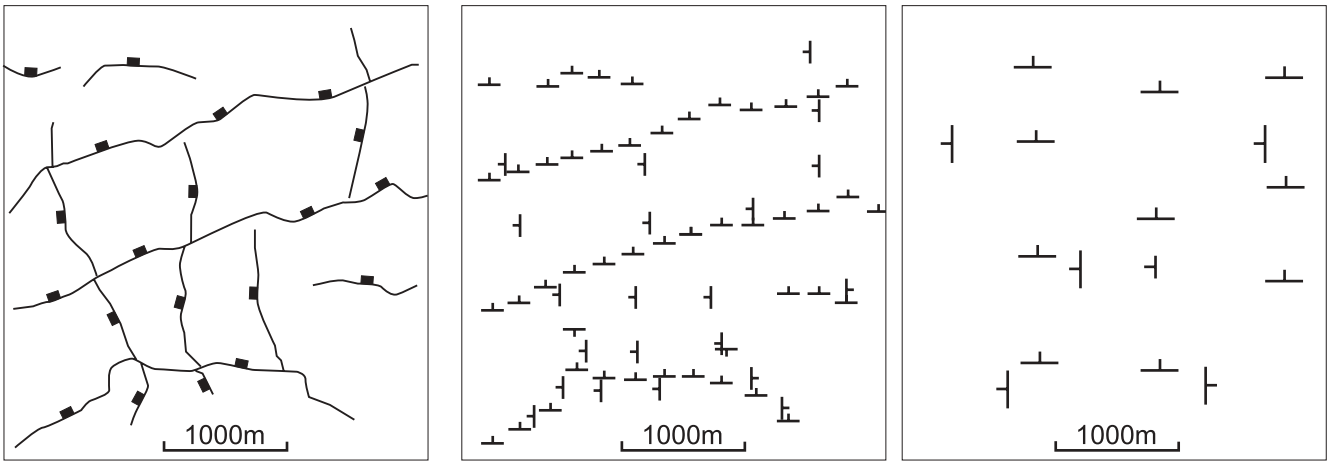

Fig. 2. The effect of survey grid spacing on the ability to map polygonal fault systems. (**a**) Fault map based on a grid spacing of 25 m by 25 m, showing a highly interconnected network. (**b**) Fault picks taken at a spacing of 250 m by 1000 m. It would be just about possible to link these picks to make a fault map with some of the elements of that shown in (**a**). (**c**) Fault picks taken at a spacing of 1000 m by 1000 m. No sensible correlation can be made with this low density of picks.

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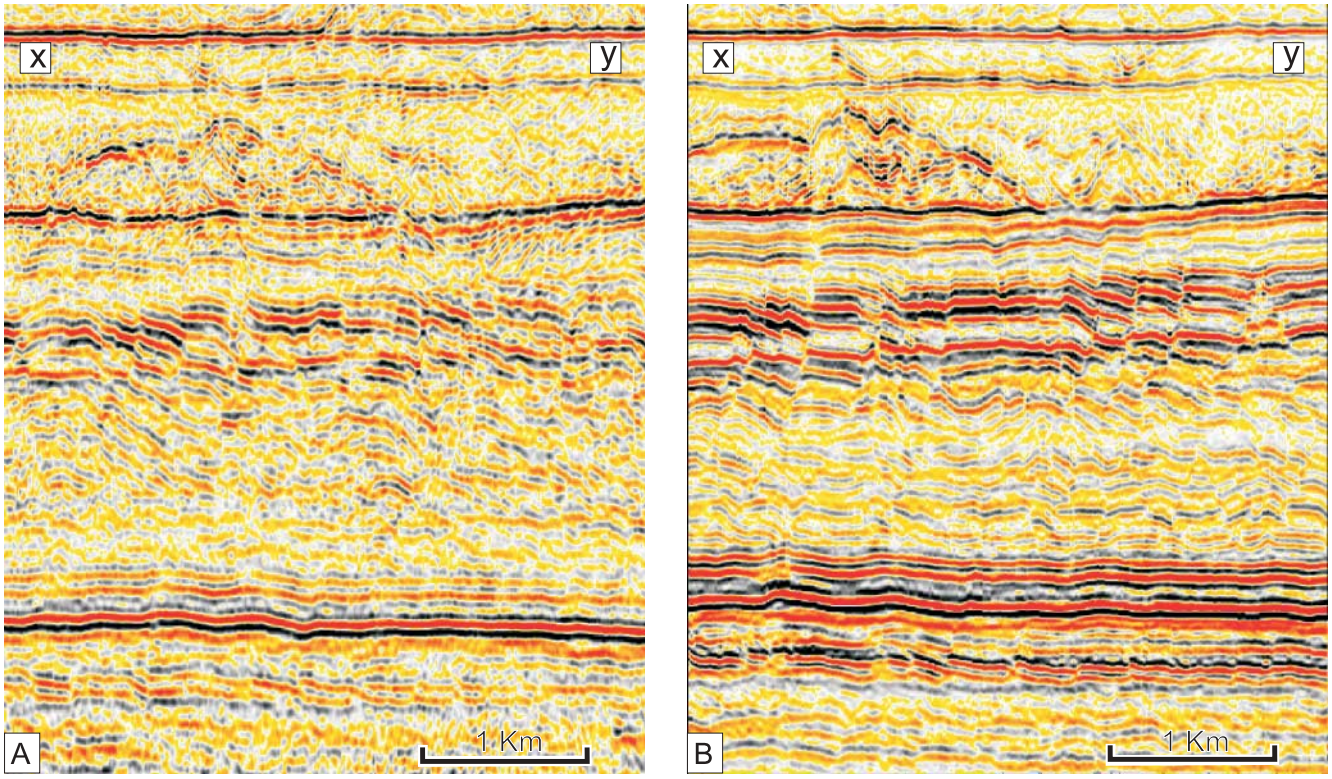

Fig. 3. Comparison of polygonal faulted interval imaged on a 2D reflection profile (**a**) and a 3D reflection profile (**b**), showing the much sharper imaging of faults achieved with the 3D seismic data.

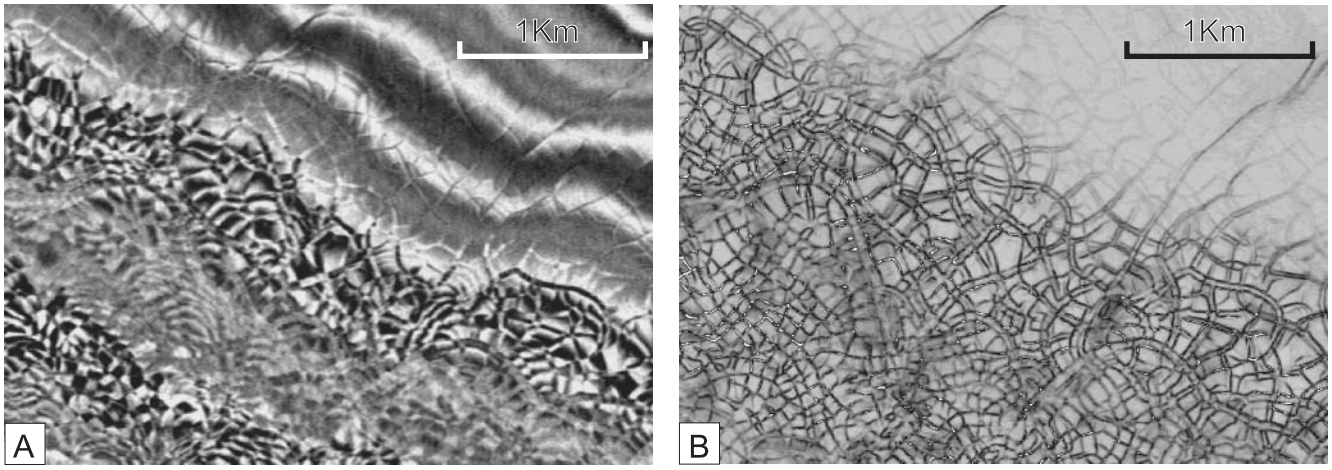

Fig. 4. Comparison of a time slice through a polygonally faulted interval (**a**) with a slice at the same position through a variance attribute cube (**b**). It should be noted that the faults can be seen on both, but the interference of stratal reflections on the time slice, striking top left to bottom right, obscures the pattern, whereas the effect of regional dip is much less pronounced in the variance cube.

to identify discontinuity in the data, and as such, was ideally suited for fault interpretation. Horizontal, or even better, stratal slicing (slicing conducted parallel to a correlated stratal reflection) of coherence volumes reveals faults in unprecedented detail, and for the study of polygonal fault systems represents a powerful additional interpretational tool, as illustrated in Figure 4, where a time slice and coherence slice through a polygonal fault system are compared. Lastly, dip or edge attributes calculated from a mapped horizon can also be a powerful tool for fault definition (Hesthamner & Fossen 1997).

Genesis of polygonal fault systems

The genesis of polygonal fault systems is poorly understood in spite of over a decade of subsurface investigations (see Cartwright *et al*. 2003, for a review). Early models were based on the

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low-quality imagery of the 2D reflection method, and advocated an evolutionary scheme involving overpressure build-up and release, and deformation related to density inversion (Henriet *et al*. 1989). With the advent of 3D seismic, models for polygonal fault system development naturally had to evolve to account for the polygonality of the network. Cartwright (1994) followed Henriet *et al*. (1989) in proposing a mechanism based on overpressure collapse, but once detailed mapping of the strain field showed that significant strains were evident and were in essence radially isotropic, the link to overpressure was dropped in favour of a more generic description of the deformation as being due to volumetric contraction (Cartwright & Lonergan 1996). This critical kinematic constraint was derived mainly because of the ability to measure strains in any orientation using the facility of defining arbitrarily oriented seismic profiles through the seismic cube.

The recognition that a significant volumetric strain was involved in the formation of polygonal fault systems was a fundamental step towards identifying a genetic mechanism. Most importantly, the realization that line length was not conserved during the deformation (Cartwright & Lonergan 1996) pointed to a radical departure from classical models of sediment compaction during the early stages of burial, which universally assume 1D consolidation as the primary process, as described by soil mechanical theory. That polygonal fault systems formed early during burial was recognized early on in the interpretation of both 2D and 3D seismic surveys. Two key observations were important in this respect: (1) the edges of the polygonal fault systems tended to occur where the stratigraphic unit thinned to $<$100 m (Cartwright 1994); (2) the upper tips were found to be associated with small synkinematic hanging-wall wedges, an observation that is clearly indicative of growth faulting at the sea bed (Cartwright 1994; Lonergan *et al*. 1998; Stuevold *et al*. 2003). It was this seismically derived argument for their formation during the earliest stages of burial that placed the deformation in a soil mechanical, rather than rock mechanical context.

More recently the debate over their genesis has intensified (Cartwright & Dewhurst 1998; Watterson *et al*. 2000; Goulty 2002; Cartwright *et al*. 2003; Goulty & Swarbrick 2005; James *et al*. 2006), possibly reflecting greater awareness of the vast lateral distribution and economic significance of these structures. In particular, the recognition that many deepwater sandstone reservoirs in the NW European petroleum province have topseals that are pervasively deformed by polygonal fault systems raises questions about the extent to which the presence of a polygonal fault systems in a seal unit compromises seal integrity (Stuevold *et al*. 2003; Shoulders & Cartwright 2004). Some large reservoirs hosting considerable hydrocarbon reserves, such as within the Ormen Lange Field offshore Norway, are themselves entirely faulted by polygonal fault systems that have propagated across the sandstones from underlying or overlying claystones, and this means there is an even more direct economic imperative to understand fault genesis (Stuevold *et al*. 2003). In the case of Ormen Lange, the polygonal faults may play a significant role in intra-reservoir compartmentalization, and knowledge of their geometry and sealing properties is thus a key part of the reservoir engineering challenge (Møller *et al*. 2004).

The significance of polygonal fault systems extends far beyond their role in hydrocarbon exploitation, however, to the broader issues involving the intrinsic permeability of the fine-grained sediments that host these extraordinary fault networks (Cartwright *et al*. 2003). These wider field of topics includes the impact of polygonal faults on radioactive waste storage in claystones (Dehandschutter *et al*. 2005), the stability of slopes with polygonal fault systems embedded into thick claystones (Berndt *et al*. 2003; Bunz *et al*. 2005), the potential for polygonal fault systems to affect strategies for extraction of methane hydrates from continental slope sediments, and the role of polygonal fault systems in controlling feedbacks in diagenesis of slope sediments. Whatever the long-term outcome of the debate on polygonal fault genesis, it seems clear that their ubiquity in continental margin settings and links to fluid flow phenomena in the shallow subsurface will guarantee continued interest in these structures for many years to come.

Pipe structures: avenues for focused vertical fluid migration

The seismic reflection method is geared primarily towards imaging gently dipping features, and vertical or subvertical features can generally only be identified if they offset or distort stratal reflections in a systematic way. This is, of course, the basis for most fault interpretation, particularly where the fault plane is too steep to produce a true reflection directly from the fault plane itself (typically when $>$50–60°). In older 2D reflection surveys, subvertical zones of disturbed stratal reflections were commonly interpreted as zones of poor data quality, or alternatively, where there were amplitude anomalies present, as caused by the effects of gas migration through the sedimentary overburden.

As noted in the introduction, seismic migration algorithms have improved greatly in the past two decades; for example, with the introduction of pre-stack depth migration (Yilmaz 2001), and with the combination of this improved imaging and the greater spatial resolution of 3D seismic data, it has become possible to delineate a number of different types of subvertical to vertical columnar structures that cross considerable thicknesses of stratigraphy in many contrasting geological settings. These columnar structures are collectively referred to here as pipes. Their importance stems from their role as potential fluid flow conduits in sedimentary basins. Like polygonal fault systems, they have been identified and described only using 3D seismic data, although they were probably observed by many seismic interpreters and either dismissed as artefacts or zones of poor data quality, or ignored because they were too small to be mapped accurately.

Pipes were first identified and linked to a genetic mechanism involving highly focused fluid flow by Løseth *et al*. (2001), who described a series of vertical columnar zones of disrupted stratal reflections using 3D seismic data from the continental margin of Nigeria. These pipes extended across $>$1000 m of mainly fine-grained sediments. They had a diameter of *c*. 100 m, and on 3D data were found to have a strikingly circular planform. The pipes terminated upwards in sea-bed pockmarks, an observation that led Løseth *et al*. (2001) to suggest that they formed by a process akin to a natural high-pressure blow-out, where methane stored in a shallow aquifer exceeded a critical pressure and the seal failed, allowing the high-pressure methane–pore-fluid mixture to bore its way to the surface. Critically, the 3D imaging was high enough in quality to allow the identification of numerous small sideways offsets in the pipes. This observation allowed Løseth *et al*. (2001) to exclude the possibility that these features were simple artefacts, as, for example, so often found to result from the scattering–attenuation effect of anomalous velocity bodies such as gas accumulations or reefs, particularly when relatively short cable lengths are used in the seismic acquisition.

By reference to field analogues, Løseth *et al*. (2001) argued that the pipes probably consisted of zones of distributed fractures

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within otherwise impermeable clay-rich sediments, and hence represented vertical pathways for fluid flow from the time of their formation. Since their first identification by Løseth *et al*. (2001), similar pipe-like structures have been observed in several other case studies where focused fluid flow can be invoked as the driving mechanism in their formation (e.g. Berndt *et al*. 2003; Bunz *et al*. 2005; Ligtenberg 2005; Cartwright *et al*. 2007).

From the increasing number of examples that have been published in the last few years, it is possible to generalize a little on the seismic expression of pipes, and some representative examples are presented in Figure 5. They are commonly columnar (Fig. 5a), but can exhibit steep conical geometry (Fig. 5b). They are best delineated by disruption of otherwise laterally continuous stratal reflections, and so are easiest to interpret confidently in highly stratified seismic facies units, such as in hemipelagites. There is occasionally evidence for local updoming and intrusion of sedimentary material within the pipe (Fig. 5c), and commonly there are distributed amplitude anomalies within or immediately adjacent to the pipe, suggestive of gas-saturated pore fluid or cementation (Fig. 5c and d).

Their detailed internal structure is poorly constrained and is almost certain to be highly variable, depending on the context, and the mode of formation. In some cases, pipes consist of zones of deformed reflections suggestive of minor folding and faulting, whereas in others they simply appear to consist of stacked pockmark craters or stacked localized amplitude anomalies that are likely to be small gas accumulations or zones of cementation, but with no resolvable deformation (Fig. 5d). It seems probable that even where there is no visible offset of reflections within the pipe, sub-seismic fracturing is likely to occur at some position within the pipe. This view is based primarily on descriptions of likely outcrop analogues from the mining geological literature, where many ore bodies are described forming within columnar breccia pipes (Bryner 1961). If this analogy is appropriate, then they would probably consist of brecciated caprock with zones of high fracture intensity, variably intruded by small dykes of

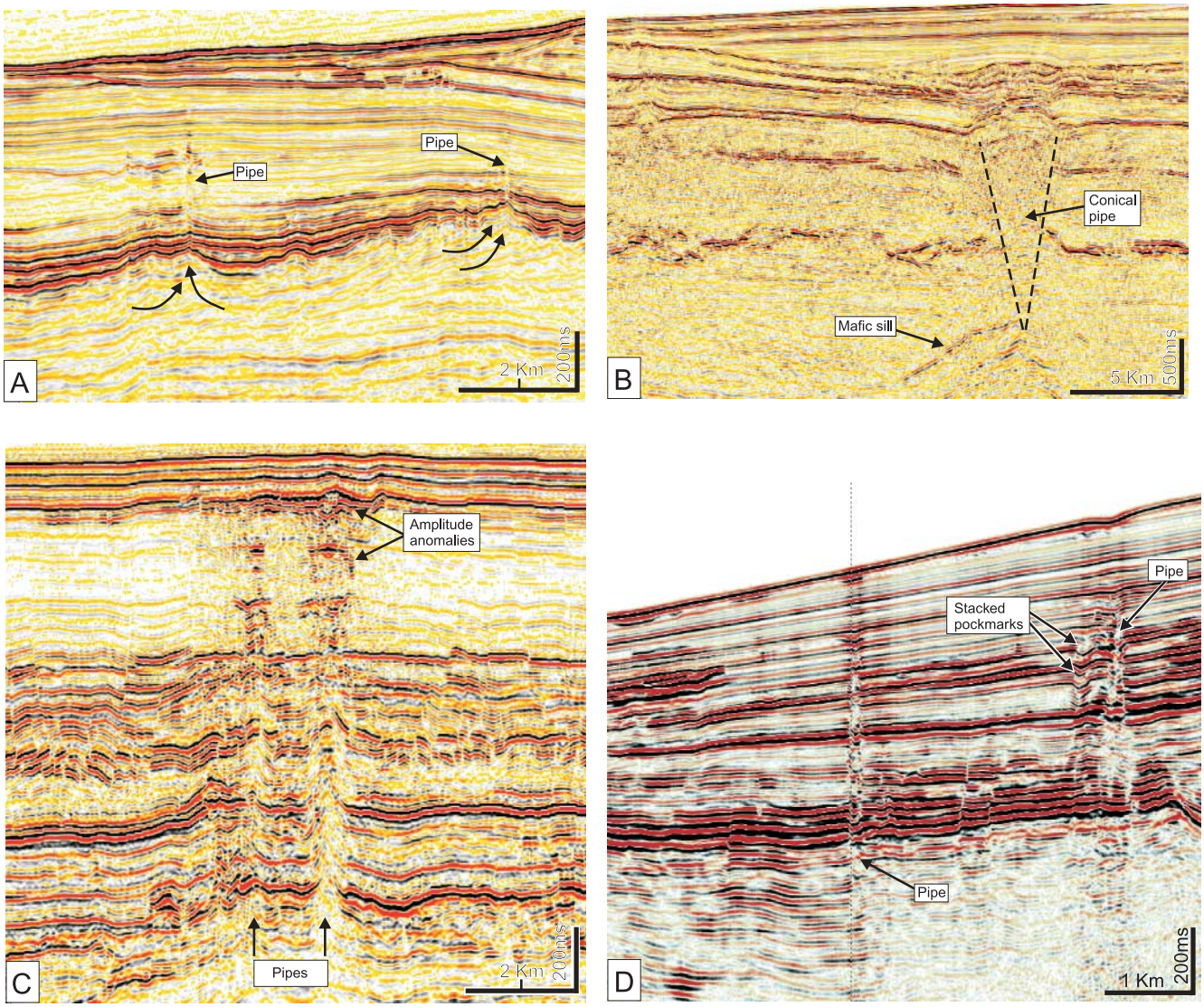

Fig. 5. Seismic expression of pipe structures. (**a**) Examples of blowout pipes from the Faeroe–Shetland Basin (data courtesy of PGS UK Ltd). (**b**) A large hydrothermal pipe from offshore Norway. (**c**) Blowout pipes from offshore Norway (data courtesy of Norsk Hydro A/S). (**d**) Blowout pipes from offshore Namibia (data courtesy of NAMCOR).

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material transported from the base, and from along the flow route. Xenoliths of caprock would probably be incorporated into the pipe structure.

The dimensions of pipes vary enormously, but even with the best 3D seismic data the interpretation of their vertical and lateral extents is highly problematic. It is usually straightforward to constrain their upper terminations, and these commonly comprise pockmark craters (either at the present sea bed or a palaeo-sea-bed datum), or sediment mounds (Fig. 5b and c). However, it is much harder to define their base, and hence the source layer whence they emanated, simply because of the problem of differentiating true disruption of strata from the downward propagation of localized imaging artefacts (scattering, velocity anomalies). In Figure 5c, for example, although the pipe can be traced confidently downward to near the base of the profile, it is not clear whether this is indeed the root zone, or whether the true source level is slightly shallower. A similar caveat applies to the interpretation of lateral extent. The true dimensions of the pipe are in most cases likely to be much less than the extent of the observed zone of stratal disruption, simply because the effects of fluid migration can infiltrate the host sediments, and result in abrupt velocity changes because of the presence of gas and/or cements (e.g. Fig. 5c).

These imaging problems are a useful reminder that even the very highest quality 3D seismic surveys have their resolution limits, and much as we would like to know the conduit dimensions and internal structure, we are unlikely to gain these specific insights from this medium. The 3D seismic data, do, however, provide the subsurface context for their occurrence, and their association with co-genetic features such as pockmarks or mud volcanoes, and these contextual observations provide a powerful research avenue to induce their origin.

Pipe genesis

Three main families of pipes can be distinguished based on their structural and stratigraphic context (Cartwright *et al*. 2007). These three families are dissolution pipes, hydrothermal pipes and blowout pipes. This first attempt at classification of pipes is largely based on an interpretation deriving from the geological context and is therefore open to modification as our understanding of the key genetic processes improves. It is nevertheless included here as a guide to the contrasting expressions of highly focused vertical fluid flow on seismic data, and as an aid to further recognition and description of these puzzling structures.

Dissolution pipes. Dissolution pipes form by dissolution of rock units at depth to form subsurface cavities that promote instability in the overburden leading to collapse (Stanton 1966; Cooper 1986). They are thus most likely to occur in areas of evaporite or carbonate karst. The dimensions of the collapse pipe are directly related to the dimensions of the solution cavity, but are also influenced by overburden strength and heterogeneity (Branney 1995).

Figure 6 shows an example on seismic data of a tall cylindrical zone of sagging, intense faulting and fracturing located above a pronounced circular depression formed in a major evaporite body. The 3D seismic data were interpreted to show that a series of similar dissolution structures were located in this basin (Bertoni & Cartwright 2005). The otherwise highly efficient evaporite seal has been breached by the localized dissolution structure, and fluids could therefore exploit this gap to migrate up through the overburden, further assisted in their vertical migration by the fracture pathways opened up in the dissolution pipe.

Hydrothermal pipes. Hydrothermal pipes form by high flux migration of hydrothermal fluids associated with certain kinds of igneous intrusions, particularly mafic sills or laccoliths (Svensen *et al*. 2004). Hydrothermal pipes are recognized on seismic data from their character as columnar or steep-sided, downward tapering conical zones of disturbed or even collapsed stratal reflections, but primarily from their direct connection with igneous sills (Fig. 7). They are generally observed to emanate from the inclined lateral margins of sills or from ridge-like junctions within sills (Hansen *et al*. 2004). They exhibit a considerable range in dimensions, with diameters from *c*. 100 m to 3 km, and heights from hundreds of metres to 2.5 km (e.g. Fig. 7). The fluids involved in the hydrothermal circulation related to these types of intrusion are derived from the magma by devolatilization, and from the host sediments by localized heating, metamorphism or simply thermal pumping of pore fluids (Einsele *et al*. 1980; Delaney 1987).

Subsurface examples of hydrothermal pipes were first inter-

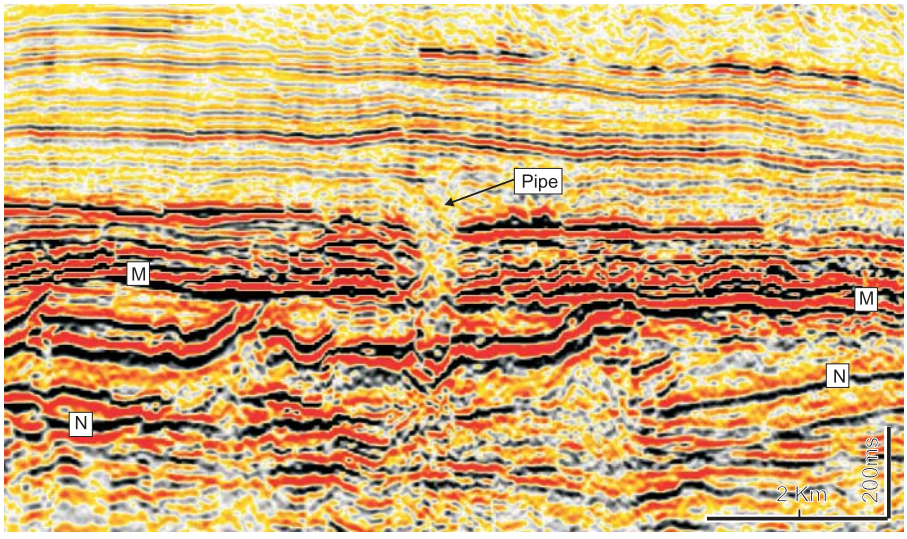

Fig. 6. An example of a dissolution pipe formed by the collapse of evaporite karst cavities developed in the Messinian evaporites of the Eastern Mediterranean (Bertoni & Cartwright 2005). M and N are top and base Messinian, respectively.

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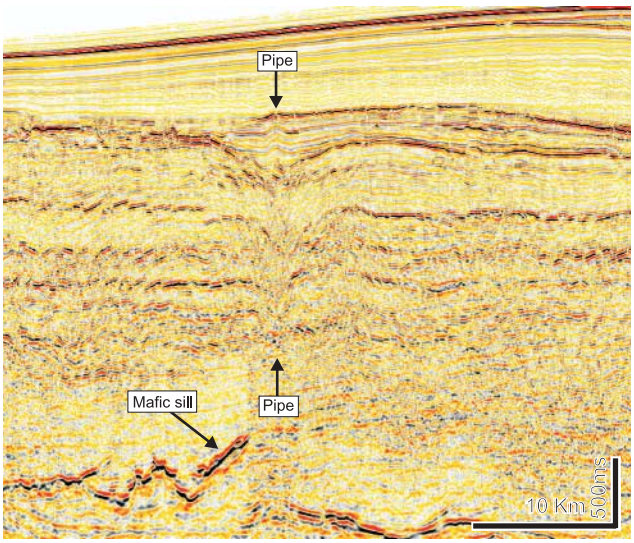

Fig. 7. Large hydrothermal pipe imaged on 2D seismic reflection profile from offshore Norway. The loss of coherent energy in the core of the collapse zone of the pipe should be noted.

preted from regional 2D seismic data (Skogseid & Eldholm 1989), but their geometry and relationship to underlying mafic sills were only recognized more recently using 3D seismic data (Bell & Butcher 2002; Davies *et al*. 2002). Subsequently, their ubiquitous development in volcanic continental margins has become more apparent (Trude *et al*. 2003; Svensen *et al*. 2004; Hansen 2004), and they can thus be predicted to occur in any basin where there is a phase of mafic intrusion in the form of dykes and sills. Hydrothermal pipes associated with mafic sills are common sites of mineralization and are known as breccia pipe bodies in the mining literature (Barrington & Kerr 1961; Bryner 1961). The many descriptions of these breccia pipe hosted ore bodies point to a catastrophic process of formation: (1) with very large fluid fluxes (Rove 1947; Sohnge 1963), (2) where fracture networks are opened within the columnar body by hydraulic fracturing and by stoping or collapse (Phillips 1972); (3) where the dynamics of fluid flow leads to pipe enlargement, wall rock abrasion and collapse (Barrington & Kerr 1961); (5) where the vestiges of the fluid flow regime are expressed in complex multiphase vein networks (Newhouse 1942).

There is abundant evidence of breccia pipes (and their fracture networks) acting as fluid flow conduits for many millions of years after the initial intrusion-related phase of hydrothermal activity (Barrington & Kerr 1961). Recent seismic evidence has also testified to the longevity of hydrothermal pipes whereby the pipe is activated as a conduit for fluid expulsion at the sea bed in a number of later discrete episodes linked to regional tectonics (Svensen *et al*. 2004; Hansen *et al*. 2005). It is thus likely that hydrothermal pipes represent an important component in the long-term hydrodynamic behaviour of many basins hosting igneous intrusions, and play an important role in vertical focusing of fluid flow through low-permeability sedimentary rock units, promoting hydrocarbon migration and ore petrogenesis.

Blowout pipes. Blowout pipes have many similarities to the other two families as regards their seismic expression, in that (1) they have similar horizontal and vertical dimensions, and (2) they are typically seen on seismic data as a columnar zone of disturbed reflections or vertically stacked localized amplitude anomalies (Fig. 5c and d). They can be distinguished, however, on the basis of their association with surface or palaeo-pockmarks (Løseth *et al*. 2001). Localized deformation of reflections in the form of small faults and folds is also commonly seen either on the margins of the columnar disturbance or within the core of the column (Fig. 5c). Blowout pipes differ from dissolution and hydrothermal pipes principally in context: they are not specifically associated with underlying igneous intrusions or with karstified units. Instead, they tend to be localized at natural leak-off points for overpressured pore fluids; for example, at the crests of structures, above gas reservoirs, or at the updip limits of aquifers. This contextual link to obvious positions of focus of overpressure stresses the link to the inferred genetic process of a high-pressure gradient driving the fluid flow in such a way as to produce the columnar conduit.

The formation of blowout pipes is poorly understood at present, as only a few examples have been described and none have been calibrated by drilling. Løseth *et al*. (2001) first linked their genesis to catastrophic breaching of top seals on shallow gas reservoirs. They can be regarded as a natural blowout pathway either to the surface or to some shallower aquifer (internal blow-out). Evidence to support the concept that these pipes represent a discrete 'blowout' event, rather than a longer-term, slower flux process is that they often vertically underlie large pockmark craters located at the surface and thus appear to connect a source region for high-pressure fluids and the site of expulsion of those fluids to the water column (Løseth *et al*. 2001). Pockmark craters overlying blowout pipes can be hundreds of metres in diameter and >50 m deep, with excavation of $>10^5$ m^3 of near-surface sediments. The excavation of such large volumes probably requires a similarly large flux of pore fluids and/or gas, although no scaling relationship linking pockmark crater volume to fluid flux has been defined. The crater morphology of the pockmarks does suggest that whatever the magnitude of the flux, it probably escaped in a single event (Hovland & Judd 1988).

The large flux inferred in the formation of some of the larger pockmarks requires a high transient permeability along the pipe, and it is for this reason that it is proposed that blowout pipes form by a combination of hydraulic fracture under elevated pore fluid pressures and by stoping or fluid-driven erosion and collapse. Importantly, the fact that they have been observed to cross over 1000 m of very low permeability units suggests that the driving processes involved in pipe development are extremely energetic, and perhaps reminiscent of the formation of igneous diatremes, where gas expansion plays a major role in fracturing the conduit ahead of the rising fluid (magma) column (Lorenz 1985). Gas expansion is almost certainly a major contributing factor in the formation of some blowout pipes because of their association with pockmarks (Hovland & Judd 1988; Løseth *et al*. 2001).

The similarities with igneous diatreme development also raise the possibility that blowout pipes represent an end member in a spectrum of sedimentary diatremes. It is conceivable that blowout pipes represent the first stage in an evolutionary sequence that can lead to the development of conduits for mud volcanoes, as the theoretical conditions are similar for both cases (Karakin *et al*. 2001), the only difference perhaps being that, in a blowout pipe, there is insufficient flux of gas-saturated mud to reach the surface and build an edifice, and the surface expression is therefore a crater, rather than a volcano. Brown (1990), for example, in discussing conduits for mud volcanoes, described pillar-shaped seismic disturbances that he inferred to have

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resulted from 'the rapid flow of pore fluids (generally water or methane) up through a sediment mass which becomes fluidized and entrained in the advecting fluids'. It is also possible that blowout pipes feed other forms of sedimentary extrusion such as sand volcanoes, and this type of pipe has been termed a fluidization pipe by Davies (2003).

Blowout pipes are commonly, but not universally, circular in planform, even when they are seen to emanate from fault planes or from linear ridge crests or pinch-outs. This circular planform is common to all diatremes, and has been elegantly explained by Novikov & Slobodskoy (1978) as a means of minimizing energy losses caused by wall friction in the contact zone between the upward flowing and expanding fluids and granular particles in suspension and the static country rock.

In many cases, 3D seismic data provide evidence that once formed, blowout pipes remain embedded within otherwise low-permeability successions as a structure of significant permeability anisotropy for long periods of time, as is indeed the case with mud volcano conduits (Morley 2003). Vertically stacked pockmarks are perhaps the best testament to this episodic behaviour as vertical fluid flow conduits. This longer-term durability of the permeability anisotropy has considerable implications for basin hydrodynamics, as is the case with all three families of pipes, and is perhaps the main point of interest when considering future research initiatives.

Diagenesis

Research into diagenetic processes has traditionally been the preserve of field and laboratory-based studies, and most of the fundamental concepts have been derived from petrology and geochemistry. A geophysical approach to the study of diagenesis seems at first implausible, but the seismic reflection method depends entirely on changes in acoustic impedance (the product of rock density and P-wave velocity), and because diagenesis often results in changes in these rock properties through, for example, changing mineralogy or cementation fill of pore space, there should be every expectation that such changes could be imaged on seismic reflection data, provided they are sufficiently extensive to be spatially imaged, and sufficiently discrete to result in a large enough acoustic impedance contrast.

One diagenetic reaction in particular fulfils these acoustic criteria; namely, the transformation of silica from the Opal A to the Opal C/T phase (Scholl & Creager 1973; Hein *et al*. 1978). This transformation involves a complex set of solution–precipitation reactions and results in a dramatic porosity reduction in the host sediments because of the dissolution of the pore framework building, biogenic Opal A, and the precipitation of the microcrystalline, pore-filling Opal C/T (Kastner *et al*. 1977; Williams & Crerar 1985). The reduction in porosity equates to an often dramatic increase in sediment bulk density over a vertical distance of only a few metres, and this in turn is expressed acoustically as a boundary with a major increase in acoustic impedance (Nobes *et al*. 1992). The diagenetic front is thus visible on seismic reflection data as a discrete reflection, which is often instantly recognizable because of its high amplitude and discordant geometry, often cross-cutting stratal reflections (Davies & Cartwright 2002).

The Opal A to Opal C/T diagenetic front (A–C/T) was first described from 2D seismic reflection profiles acquired during research cruises linked to the earliest drilling campaigns of the Deep Sea Drilling Project (Scholl & Creager 1973; Hein *et al*. 1978). These early investigations were located in deep-water settings on lower continental slopes or abyssal plains, where sedimentation rates were slow, where the sediments were undeformed, and where accordingly, the seismic reflection from the A–C/T was generally parallel to the present-day sea bed. As a result of this parallelism to the sea bed, the diagenetic reflections were often described as a type of bottom-simulating reflector (BSR), and much discussion focused on distinguishing them from other types of BSR; namely, those associated with gas hydrates (Lonsdale 1990).

During the 1990s, as petroleum exploration moved increasingly into deep-water regions of continental margins, regional 2D seismic reflection surveys were acquired in areas of high biogenic silica production, such as offshore Norway. These surveys imaged spectacular examples of the A–C/T reflection over vast distances, and it rapidly became apparent that it was not parallel to the sea bed, and was in fact highly discordant to host stratigraphy (Skogseid & Eldholm 1989; Brekke 2000). More recently, 3D seismic surveys acquired for deep-water exploration purposes have been used to map the geometry of the A–C/T reflection, and this high-resolution mapping has stimulated a new approach to the study of diagenesis.

In the past few years, 3D mapping of the A–C/T across large parts of the NE Atlantic basins offshore UK and Norway has revealed a far more complex geometry than was appreciated from the earlier 2D reflection data. Over most of the margin, from the Rockall Basin in the SW to the Vøring Basin in the NE, the A–C/T reflection is hosted within laterally extensive and polygonally faulted biosiliceous mudstones (Cartwright & Dewhurst 1998). Over *c*. 90% of the total mapped areal extent of the A–C/T reflection (>200 000 km^2), it is relatively smooth at a large scale of observation, but closer inspection shows it to be systematically offset by most of the polygonal faults in the host unit (Fig. 8). Older vintages of 2D reflection data were not able to image these small fault offsets, and hence the A–C/T reflection appeared smoother than it is in reality, once the same section can be seen using 3D seismic data. A comparison between a 2D and 3D reflection profile along the same section demonstrates this imaging issue very clearly (Fig. 9). The high quality of the 3D imaging shows that the offset of the A–C/T reflection across each polygonal fault is much smaller than the true structural offset of the host stratigraphy (Fig. 9b). This relationship was initially interpreted to imply that the faulting

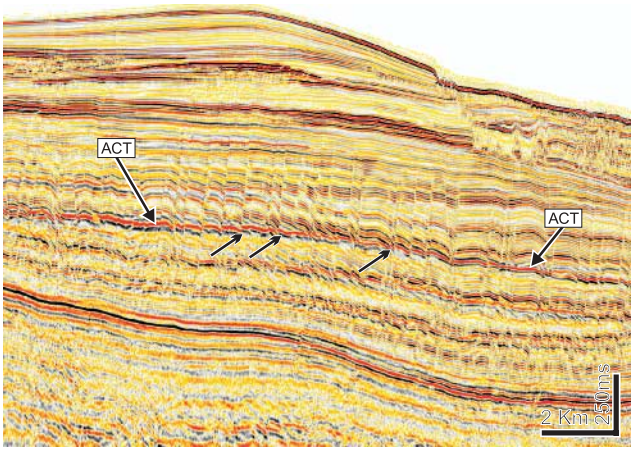

Fig. 8. A 3D seismic reflection profile showing the faulted nature of the Opal A–Opal C/T diagenetic reflection (ACT) from offshore Norway (data courtesy of Statoil A/S). The small arrows indicate the discrete offset of the Opal A/CT reflection across faults.

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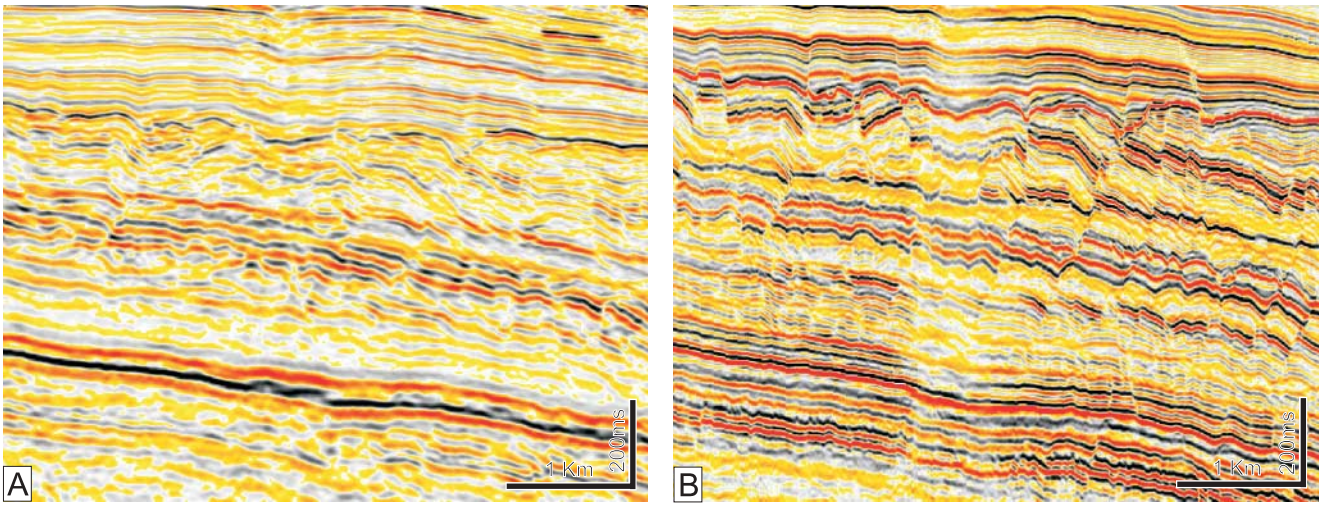

Fig. 9. Comparison of a 2D (**a**) and 3D (**b**) seismic reflection profile across the same transect of a biosiliceous interval from offshore Norway, showing the difference in imaging of the Opal A–C/T diagenetic reflection (data courtesy of Statoil A/S).

post-dated the diagenetic transformation (Davies & Cartwright 2002), but the same relationship could occur if the displacement rate of the faults was greater than the rate of diagenetic front advancement upwards through unconverted Opal A rich succession.

Over a relatively small percentage (<5%) of the total extent of the A–C/T, in three separate areas of the margin (Faerøe–Shetland, Møre and Vøring Basins), the geometry of front is not faulted, but instead has a morphology characterized by polygonal ridges and depressions, at a wavelength of 1–1.5 km (Fig. 10) (Davies & Cartwright 2007. This irregular cross-sectional geometry was first identified using 2D reflection data (Vogt 1997), but the extraordinary polygonal planform was only identified once 3D seismic data became available in the specific areas where this pattern was developed (Davies *et al*. 1999). Initial ideas on the origin of this anomalous pattern were based on density inversion cells linked to fluid expulsion during diagenesis (Davies *et al*. 1999; Davies & Cartwright 2002), but further mapping suggested instead a process of differential front advancement with concomitant differential subsidence of the overburden (Davies 2005).

Comparing the polygonal cellular structure of the A–C/T (Fig. 10) with typical polygonal fault patterns (e.g. Fig. 1), it might be tempting to infer some similarity of process, particularly as there is a geographical coincidence of the two phenomena and a similarity in length scale. Indeed, Davies (2005) proposed that the differential front advance might itself be due to focused fluid flow upwards along polygonal fault planes, and the polygonal planform of the A–C/T was thus inherited from the underlying polygonal fault system. One problem with this model is that there are many more polygonal fault planes than there are polygonal diagenetic cell boundaries, the cell boundaries do not sit vertically above polygonal faults, nor do cell centres sit uniquely above faults or fault intersections, and finally there are

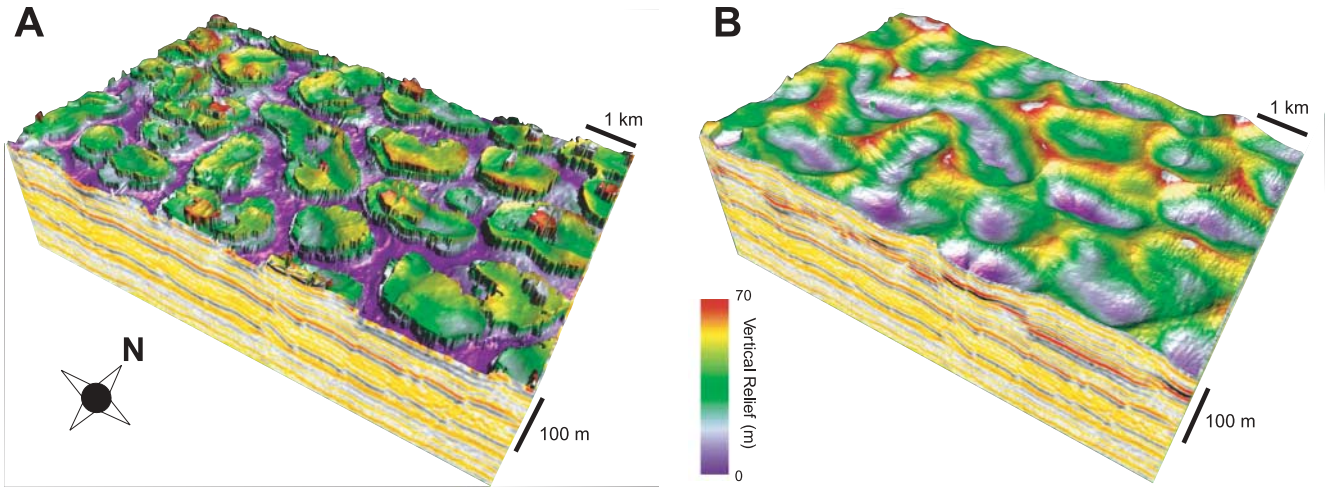

Fig. 10. Complex pattern of the irregular morphology of the Opal A–C/T reflection as mapped using 3D seismic survey, offshore Norway (data courtesy of Statoil A/S). Relative relief is shown from red (high) to purple (low). (**a**) Two-way travel time (TWT) structure map of the diagenetic reflection. (**b**) TWT structure map of horizon in the Opal A rich interval just above the diagenetic reflection. (From Davies & Cartwright 2007.)

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polygonal A–C/T cells above stratigraphic units with no polygonal faults deforming them. Although the origin of the polygonal A–C/T morphology is thus still open to debate, what is clear is that such a morphology has many parallels to irregular reaction fronts at many smaller scales (Davies & Cartwright 2007), from the metre scale of the typical carbonate at cemented layer outcrop (Seilacher 2001) to the atomic scale of laboratory controlled reactions (Sachs *et al*. 2001). Further research combining the resolving power of the 3D seismic method with detailed petrological and geochemical analysis of borehole data will be necessary to resolve the debate on the origin of this extraordinary pattern, and will thereby shed light on other poorly constrained aspects of the A–C/T transformation.

In conclusion, the ability to map a diagenetic front on a basinal scale (>10 000 km^2) offers a novel method for investigating rock–fluid interactions during a major diagenetic transformation, simply because the spatial resolution of *c*. 25 m combined with the large areal extent of recent 3D seismic surveys allows the reaction front to be correlated across large areas of basins, where critical parameters such as time, temperature, host rock lithology, pore fluid chemistry and hydrodynamic context are laterally variable, and can thus be correlated with any changes in the morphology and structural position of the front. This type of basin-scale analysis of a diagenetic front is simply not possible using outcrop data, because of the limitations of outcrop extent and continuity. The Opal A to Opal C/T transformation is fortuitously ideal for this seismic approach to diagenesis, because of the unusually limited vertical zone over which the transformation occurs, and the resultant discrete seismic reflection produced by the reaction front. Although discrete reflections have not been reported for other regional-scale diagenetic reactions such as the smectite–illite transformation, the 'seismic diagenetic' investigation of the Opal A to Opal C/T transformation may nevertheless result in insights that can be applied to the analysis of diagenesis in general.

3D seismic data and basin analysis: quo vadis?

The examples reviewed above of the contribution that 3D seismic surveying has so far made to our understanding of processes in sedimentary basins are only a small fraction of the full spectrum of research over the past decade or so. Many additional examples of fluid–rock interactions have been documented from 3D seismic data at scales or with geometries that would not have been suspected from purely outcrop- or laboratory-based studies. Advances in rock physics over the last decade, for example, have led to much improved imaging of hydrocarbon fluids in the subsurface and this has spawned a new era for seismic applications in the form of 4D seismic imaging. Repeat surveys over the same area are now increasingly being used to detect the movement of hydrocarbons on a production time scale, and to assist in targeting unswept hydrocarbons (Verbeek *et al*. 1999), or even to monitor the migration of sequestered CO_2.

Three-dimensional seismic surveying has been directly responsible for the opening of novel research avenues in diverse aspects of soft-sediment deformation. These include an extensive set of studies on large-scale sandstone intrusions (e.g. Dixon *et al*. 1995; Lonergan & Cartwright 1999; Lonergan *et al*. 2000; Molyneux *et al*. 2002; Huuse & Mickelson 2004; Huuse & Cartwright 2004; Shoulders & Cartwright 2004). Other examples of large-scale soft-sediment deformation phenomena include basin-scale development of density inversion and differential loading (Davies *et al*. 1999; Davies 2003), large-scale slumps and slides (Huvenne *et al*. 2002; Bunz *et al*. 2005; Frey Martinez *et al*. 2005, 2007), and mud diapirism and volcanism (Van Rensbergen *et al*. 1999; Graue 2000; Van Rensbergen & Morley 2003; Davies & Stewart 2005; Hansen *et al*. 2005).

The analysis of shallow hazards along continental margins has become increasingly recognized as being critical for resource exploitation in deep-water settings and for a more general understanding of linkages between fluids and slope stability. Three-dimensional seismic data have been instrumental in progress in our understanding of linkages between fault slip and fluid flow during growth faulting (Dugan & Flemings 2000), and in the association between gas hydrate dissociation and slope stability (Bunz & Mienert 2004; Bunz *et al*. 2005). These recent studies illustrate how far our perception of soft-sediment deformation and fluid flow has changed in only the last decade, and point to far greater potential impact of 3D seismic data on our understanding of linkages between basin processes.

Beyond the realm of aqueous and hydrocarbon fluids, there is considerable potential for 3D seismic data to illuminate the migration of magmatic fluids through the crust, through the study of intrusions and hydrothermal effects of intrusions. A series of recent studies of igneous sills provide excellent examples of the optimum use of 3D seismic data to address problems that were unresolved because of the lack of 3D geometrical constraints offered by outcrop geology (Smallwood & Maresh 2002; Hansen *et al*. 2004; Trude *et al*. 2003). Igneous sills are very well imaged on 3D seismic data because of their large impedance contrasts to the host sediments, and hence are relatively straightforward to interpret. This has meant that the 3D geometry of sills can be defined with considerable accuracy, and this has led to several novel conclusions about the interactions between sills and their host rocks as well as the fundamental mode of emplacement itself. Three-dimensional seismic data also allow the interrelationships between sills to be mapped in detail (Hansen *et al*. 2004; Cartwright & Hansen 2006).

In conclusion, the use of 3D seismic data as a research tool is essentially in its infancy. As more and more research results based on 3D seismic data are published, however, we can expect the usage of this medium to grow, and this growth will be to a large degree rooted in the enhanced mapping capabilities provided by access to large 3D seismic surveys.

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