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Three-dimensional seismic imaging of a dynamic Earth

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Seismic imaging is the most important tool for investigating the interior of the solid Earth. Over the last 20 years, a major advance has been the rapid development and application of three-dimensional seismic reflection technology. Routinely used by the hydrocarbon industry to aid exploration for, and extraction of, oil and gas, this three-dimensional imaging technique is now ripe for exploitation on a global scale. Seismic reflection surveying uses acoustic or sound energy, which is easily transmitted through solid rock. Where rock properties change at depth, some of this energy is reflected back towards the surface and recorded. Seismic data are most easily collected at sea, where a vessel tows a long streamer of hydrophones in a series of parallel traverses. Acoustic waves are generated by large airguns suspended in the water; reflections, which return from depths of up to 100 km, are recorded by the streamer. Since the 1960s, many important scientific breakthroughs have been made using two-dimensional seismic imagery. More recently, three-dimensional seismic surveying has become cheaper and coverage has rapidly increased. A typical three-dimensional survey generates around 300 billion bytes of information, which, after sophisticated signal processing, yields a cube-shaped image of the subsurface. With this unique probing ability, we can map the three-dimensional subsurface architecture of continental margins where repositories of sedimentary rock contain an important record of how our planet has behaved over millions of years. We can also image the detailed pattern of deformation within these rocks. Seismic imaging is especially powerful because it contains a record of the fourth dimension: time. Other time-dependent processes, such as the movement of magmas, hydrocarbons and water through the pores of rocks, can be monitored by repeated three-dimensional surveying. Seismic imaging is the key to unravelling elusive yet fundamental processes that keep our convecting planet alive.

Keywords: geophysics; seismic imaging; sedimentary basins; hydrocarbons

1. Introduction

There is widespread acceptance that horizontal movement of rigid plates at the Earth's surface is driven by slow convection currents deep within the mantle. Broad constraints can be placed on the nature of mantle convection using fluid mechanical considerations and other indirect observations (Fowler 1990). Frustratingly, the rigidity of the lithospheric plates, which are 120 km thick, prevents us from resolving temporal and spatial details of the convective pattern below.

A potential means of learning more about processes within the deep Earth is to exploit the fact that the convective upwelling of hotter, and downwelling of cooler, mantle material causes subtle vertical motions of the Earth's surface. Regional uplift and sinking are indirectly and imperfectly recorded by erosion of the land and redistribution of sediment by fluvial drainage systems. Since uplift is eventually removed by erosion, the most complete record of this complex process is preserved in large depressions called sedimentary basins.

Here we examine the structure of sedimentary basins and show how recent technological developments have generated spectacular images of their subsurface structure on a variety of scales, from tens of kilometres to tens of metres. Within sedimentary basins, three-dimensional images reveal a range of phenomena: large-scale tilting; folding and faulting; the details of sedimentary infill; and the movement of fluids through rocks. What makes the three-dimensional seismic technique so powerful is that it is not just a static image of the Earth today; it contains an indirect record of the fourth dimension: geological time. Analysis of amalgamated three-dimensional datasets worldwide could help to quantify the spatial and temporal variation of vertical motions of the Earth's surface and, by inference, of mantle convection.

2. The seismic image

The seismic technique uses sound waves that are transmitted through the Earth. In October 1849, an Irish engineer called Robert Mallet carried out the first controlled-source seismic experiment, on Killiney Beach near Dublin. His energy sources were 25 lb charges of gunpowder buried at 6 ft depth, and the resultant seismic waves were detected using his home-grown 'seismoscope': a trough of mercury upon which was projected the image of a pair of cross-wires. By the turn of the century, seismic theory was largely developed, but instrumentation remained inadequate. Significant advances in seismic technology were made after World War II, when simple two-dimensional arrays were used to make poor quality, noisy profiles through the Earth's crust. The crucially important 'common depth point' method, which underpins all modern seismic reflection experiments, was patented by scientists from the Massachusetts Institute of Technology in 1956. This method was quickly embraced by the hydrocarbon industry and rapid technical advances followed. Routine three-dimensional seismic acquisition and processing has been developed over the last 20 years (Yilmaz 1987; Brown 1996).

The cheapest and best quality seismic data are collected at sea (figure 1). Sound waves are generated by a source suspended in water depths of 5–10 m off the ship's stern. Most sources consist of several tuned arrays of powerful airguns; each airgun can have a capacity of *ca.* 250 in^3, and so four arrays with eight guns per array gives a total of 8000 in^3. The source is primed with compressed air at *ca.* 2000 lb in^{-2} and fired at intervals of 10–20 s, equivalent to *ca.* 12 m spacing on the seabed. A vibrating bubble of compressed air is generated and the resultant shock wave travels sub-vertically through the seabed into the subsurface. The source energy is *ca.* 170 000 J, but only *ca.* 3% is converted into acoustic energy.

Although most of this energy is transmitted straight through rocks, a proportion is reflected at interfaces between different rock types, where density and acoustic

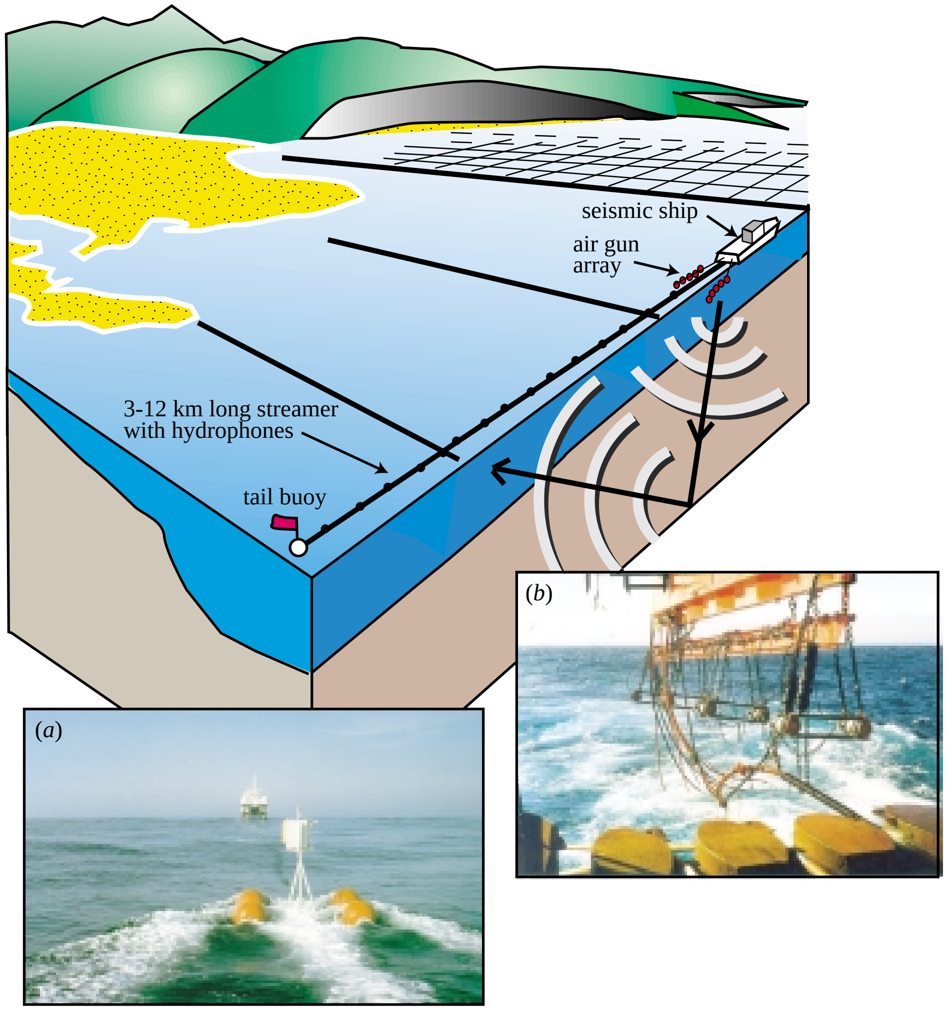

Figure 1. The essential elements of a seismic reflection experiment: airgun arrays suspended 5–10 m below the surface; oil-filled streamer with hydrophones towed in a straight line and maintained at 10–20 m depth by electronic fins; active tail buoy. The grid of dashed lines represents a complete two-dimensional survey. Photographs: (*a*) view of the ship's back deck from an active tail buoy while floating streamer is being deployed; (*b*) one array, consisting of four pairs of airguns, being deployed off the back deck. Note air hoses feeding guns from onboard air compressors. Photographs courtesy of Schlumberger and Horizon.

velocity change abruptly. Reflections travel back up through the water layer where they are recorded by hydrophones, located at intervals on a long streamer towed in a straight line behind the vessel. In two-dimensional experiments, one streamer with a length of 3–12 km is used. In three-dimensional experiments, many parallel traverses must be carried out: it is more efficient to collect swathes of data by towing 6–12 streamers, each separated by *ca.* 100 m from its neighbours. Ensuring that a large number of streamers remain straight and parallel to each other is difficult and three-dimensional vessels rarely tow streamers that are longer than 3 km.

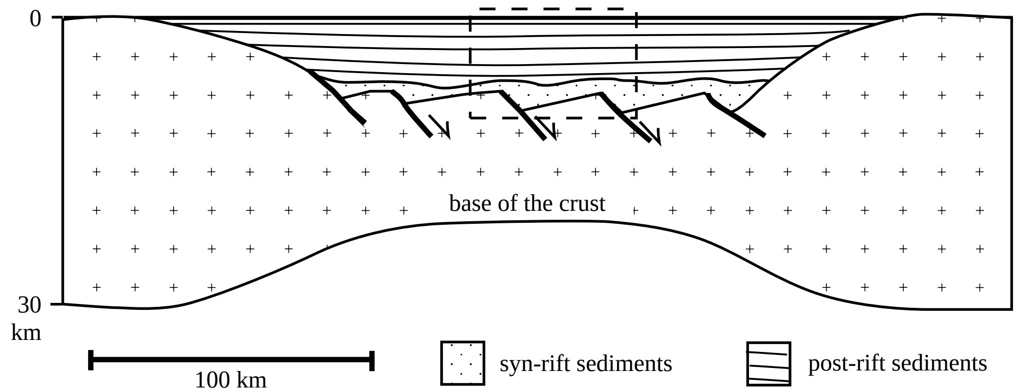

Figure 2. A sketch of a sedimentary basin that has formed by lithospheric stretching. The upper crust stretches by brittle faulting, while the hotter, lower crust and lithospheric mantle deform by plastic creep. Once stretching ceases, the region gradually subsides and fills with sediment. Dashed rectangle indicates location of figure 3*a*.

Hydrophones are grouped into recording channels: a 3 km long streamer has up to 240 channels. Signals returning from the subsurface are weak compared with the ambient noise generated by waves and other vessels. This problem is solved by collecting a great multiplicity of data, which are later added or stacked together to improve, considerably, the ratio of signal to noise. A typical three-dimensional survey covers *ca.* 10 km^2: if eight cables are towed, a total of 10 800 shots are fired and each shot is recorded by 8×240 channels. The resultant 20 million seismic records are sampled every 2 ms for a total of 8 s. Every sample is represented by 4 bytes of information and so a total of 320 Gb is acquired. Once processing is complete, this enormous volume of data is reduced to several gigabytes.

The physics that underpins seismic imaging is based upon classical wave theory and was largely developed by the turn of the (last!) century. The real power of the method, however, is our ability to stack an astonishingly large number of similar records together in order to extract meaningful signals from the Earth. If n seismic records are stacked together, the signal-to-noise ratio is increased by $\sqrt{n}$. Successful stacking requires a reliable energy source, which can be fired thousands of times without needing maintenance, and a large number of equally reliable hydrophones. Sufficient computing power is then required to record and process hundreds of gigabytes of data. Large sums of money are involved: a typical three-dimensional survey (*ca.* 50–100 km^2) costs about a million dollars to acquire and process.

The final seismic reflection volume is, essentially, an acoustic scan of the solid subsurface. The laterally continuous reflections that we see come from compositional layering of rocks at depth. Amplitudes of these reflections are related to small changes in acoustic velocity and density. These changes are caused by variations in the physical properties of rocks, especially composition and porosity. Seismic data also contain important information about the nature of fluids trapped within the pore spaces of rocks.

These cubes of data are examined in several different ways. Vertical slices through the cube are not exactly geological cross-sections: seismic imaging is analogous to echo sounding and the vertical axis is measured in the number of seconds taken to

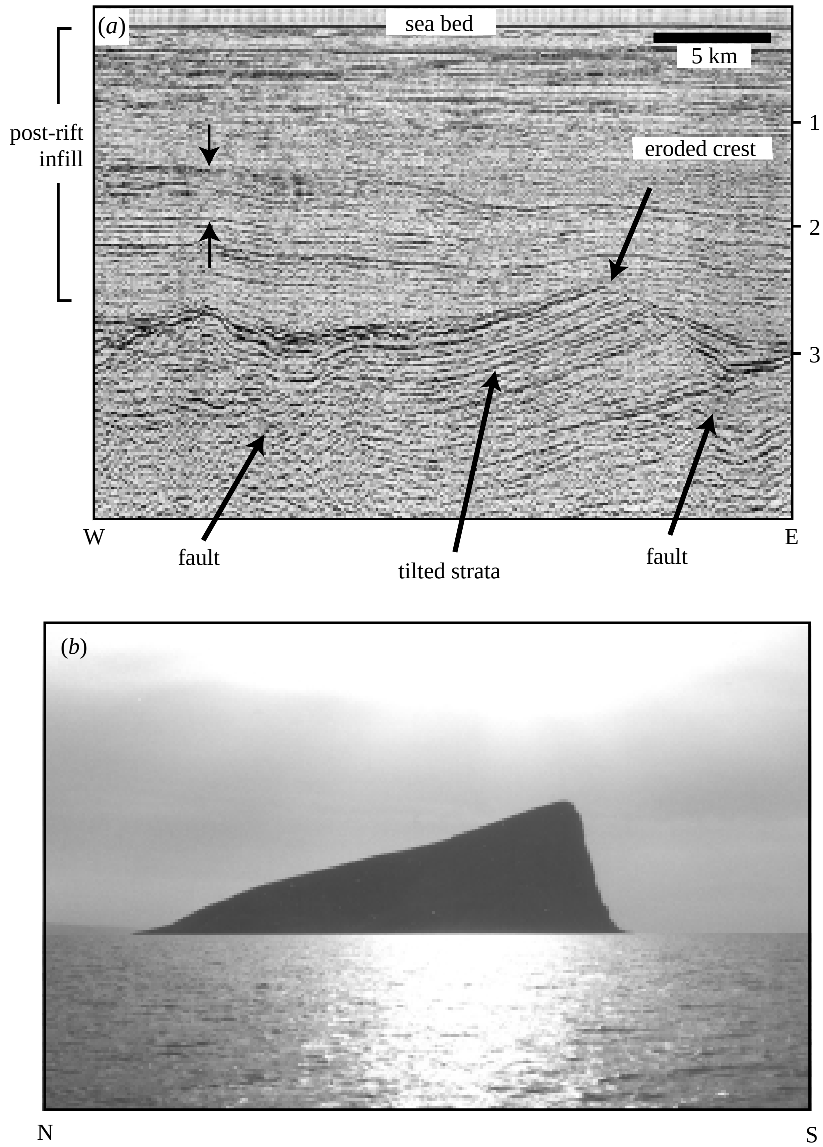

Figure 3. (*a*) Cross-section from the North Sea Basin, which formed by lithospheric stretching during Late Jurassic times (around 150 million years ago). Toward the base of the section, tilted blocks are separated by normal faults spaced 25 km apart. These rotated blocks demonstrate that the Earth's crust has been stretched. The crest of one block shows clear evidence of erosion. Some sedimentary layers were deposited during stretching when they were faulted and tilted. Most of the layered sediment was deposited during the cooling phase when stretching had ceased (labelled 'post-rift'). Submarine fan system, indicated by vertical arrows, developed during the Early Cenozoic (50–60 million years ago) when sediments were being eroded from the newly emergent Scottish Landmass. (*b*) Silhouette of Piperi located between Kithnos and Serifos in the Cycladic Islands, Aegean Sea. This wedge-shaped island is 214 m high and represents the uplifted crest of a fault-bounded block. Numerical modelling demonstrates that crestal uplift can occur during the early stages of lithospheric stretching.

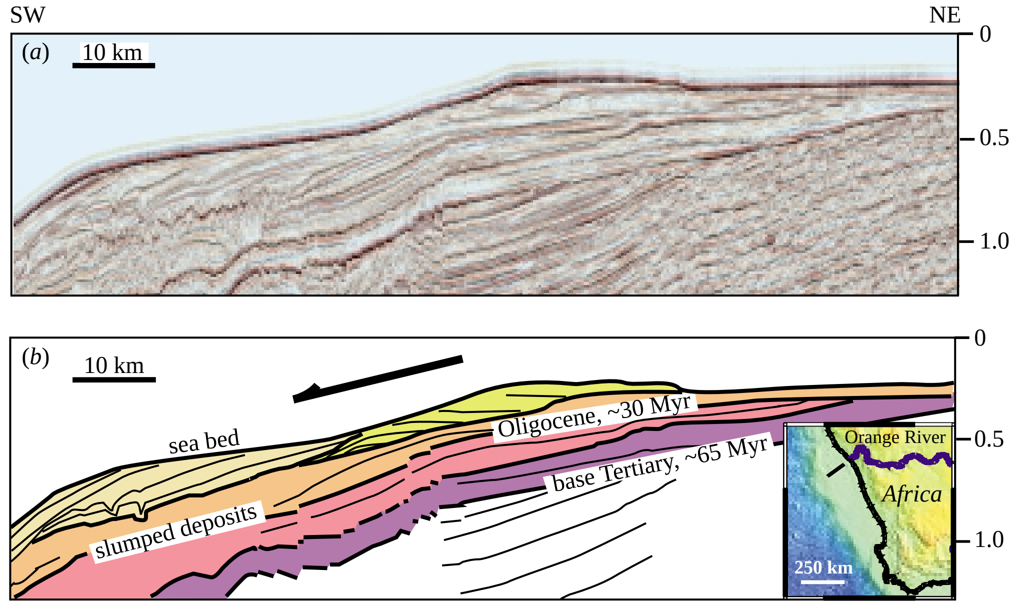

Figure 4. (*a*) A vertical cross-section through sediments deposited at the mouth of the Orange River, southern Africa (inset). Note the distinctive wedges, which reflect spatial/temporal variations in sediment supply and/or changes in relative sea level. (*b*) A schematic interpretation delineating individual packages of sediment that built out onto the continental shelf over the last 60 million years. Data courtesy of Namcor and Schlumberger.

travel down to a particular horizon and back. This 'two-way travel time' is converted to depth by using independent information about acoustic velocities. However, for the purposes of this article, you can regard vertical slices as depth cross-sections. Vertical resolution (the ability to discriminate between adjacent layers) depends upon the frequency content of the energy source and upon the filtering properties of the Earth. If the average frequency is 50 Hz, vertical resolution is *ca.* 15 m. Horizontal slices are analogous to geological maps except that filtering properties of the Earth cause horizontal resolution to decrease with depth. At 3 km depth, horizontal resolution is *ca.* 300 m and smaller geological features scatter acoustic energy instead of reflecting it. Because of the large volumes of data in a three-dimensional survey, computer workstations are an essential tool for analysing and interpreting the data. Visualization software is now used routinely to allow geologists to view the whole dataset as a cube, pan through it, rotate and cut it at any angle and rapidly form a picture of the subsurface geology.

3. How do basins form?

About 70% of the surface of the continents is covered in more than 2 km of sedimentary rock. The largest accumulations are in sedimentary basins located in continental interiors and on the continental margins. The size of sedimentary basins varies considerably but a typical example covers several hundred thousand square kilometres. Sedimentary basins are of enormous economic importance: many contain significant quantities of oil, gas and coal as well as minerals. They have acted as major sedi-

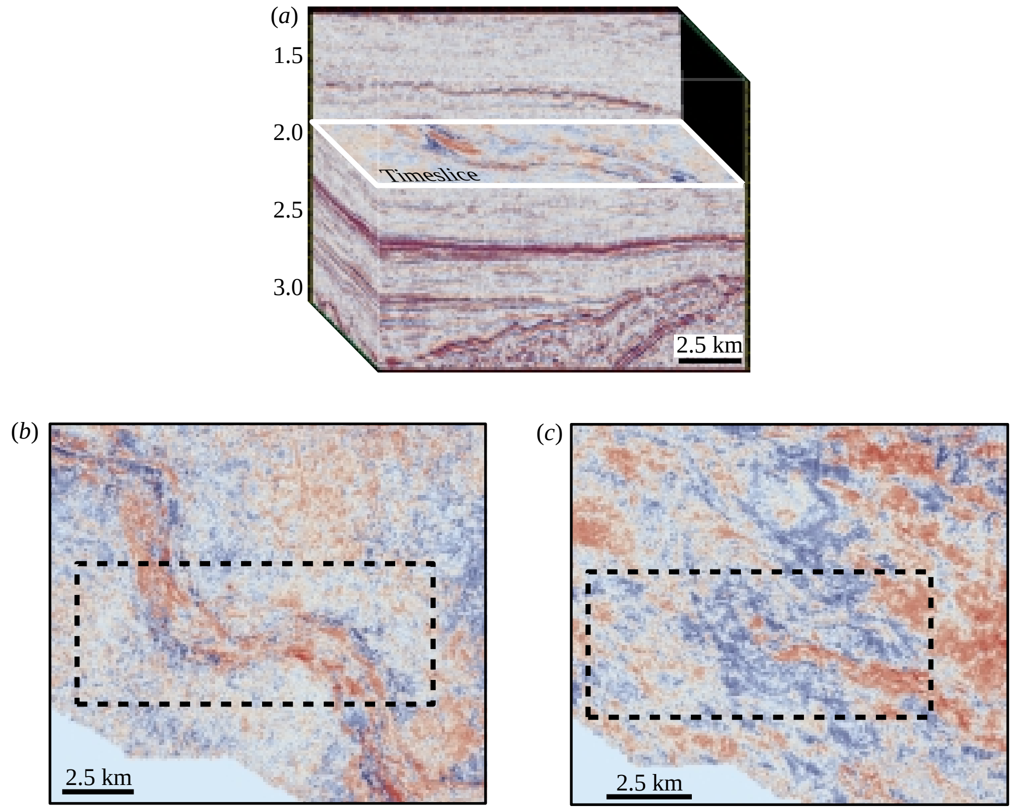

Figure 5. (*a*) Cube of seismic data from the North Sea (*ca.* 140 km^3) cut away to reveal internal geometry. Orthogonal vertical sections show tilted blocks (see also figure 3). A horizontal slice *ca.* 2 km beneath the seabed shows a meandering submarine channel, which is infilled with sand and surrounded by muddier sediment. This channel developed on a gently sloping surface during the Early Cenozoic (approximately 55 million years ago) on a sloping surface. Sediment within the channel was transported from the west, where it was shed from an emergent landmass. Note how difficult it is to see the channel in vertical section. (*b*) A horizontal slice *ca.* 40 m higher than the previous slice, whose position is marked by a dashed rectangle. Note the well-developed meandering channel system, its scale, and the detailed internal geometry. (*c*) A horizontal slice *ca.* 250 m deeper than the first slice. At this earlier time the channel system was broader and more linear. Data courtesy of Conoco.

ment sinks over tens to hundreds of millions of years and contain a unique record of temporal and spatial changes in surface processes (e.g. vertical motions, drainage systems, climate). These repositories are the most important source of information about how the Earth's surface has evolved through geological time. Thanks to the efforts of the hydrocarbon industry, most sedimentary basins have been drilled down to depths of at least 4 km. The composition and age of different sedimentary layers are determined from rock chippings collected during drilling. This information is used to calibrate seismic images.

The North Sea Basin, located between the British Isles and Scandinavia, is a typical example of a sedimentary basin. It contains up to 7 km of infill, which mostly consists of layered sand and mud. It is surprising that such a large amount of sediment lies beneath the shallow waters of the North Sea and even more surprising that this basin was only discovered in the 1960s. The origin of this accumulation was a puzzle until the advent of high-quality two-dimensional seismic data and intensive drilling from the 1960s onwards.

We now have a good quantitative understanding of sedimentary-basin formation. Many, but not all, basins form by stretching of the Earth's lithosphere: the cold 120 km thick layer that forms the rigid plates (McKenzie 1978). During stretching, the top 10 km of the crust extends by brittle failure on faults (figure 2). Fault-bounded blocks often rotate and look like tilted books on a shelf. The lower crust and the rest of the lithosphere are hotter and probably deform by plastic or ductile flow. Some sedimentary deposition takes place during stretching and volcanic activity is also common. Once stretching ceases, large-scale cooling and contraction occur and the Earth's surface slowly subsides over a period of around 100 million years (figure 2). A sedimentary basin is born as this depression grows and fills with sediment transported by rivers from eroding landmasses elsewhere.

This simple model is based on observations from the actively stretching Aegean Sea and from the North Sea. It has been carefully tested using equations that predict the subsidence pattern through time. Figure 3*a* is a typical two-dimensional image from the North Sea Basin, which formed by extension during the Late Jurassic period (approximately 150 million years ago). At the bottom of the basin, faulting and tilting of strata are clearly visible. The crests of these tilted blocks were modified by erosion during stretching. The actively stretching Aegean Sea is an important present-day analogue: many wedge-shaped islands protrude above sea level, and these islands are the emergent crests of tilted blocks bounded on the steeper side by active faults (Jackson 1987; figure 3*b*). In time, erosion will blunt these sharply defined crests. The most striking feature of the North Sea Basin is the large thickness of sediment deposited during the later cooling phase: *ca.* 4 km of layered muds, sands and chalk blanket the Jurassic fault blocks with near-parallel strata (see figure 3*a*).

Seismic surveys in the North Sea are typically recorded to 6 s two-way travel time, which is equivalent to *ca.* 10 km depth: ideal for studying the geometry of sedimentary infill. Adjacent three-dimensional surveys can be merged to give a combined three-dimensional coverage of several thousand square kilometres. The North Sea and other major hydrocarbon provinces, such as the Gulf of Mexico, now have almost 'wall to wall carpeting' of three-dimensional seismic coverage. Deeper two-dimensional surveys with recording times of up to 15 s (*ca.* 40 km) have been acquired to trace faults to greater depths and to demonstrate that the crust beneath the North Sea is thinned in accordance with the predictions of the stretching model (Klemperer & Hobbs 1991).

4. How do basins fill?

Basin infill is a large and complex subject, and our treatment in this overview article is necessarily incomplete. Besides carbonate deposits, such as limestone and chalk, the most important sources of infill are rivers that carry great quantities of sand and mud from continental interiors into basins and onto continental margins (*ca.* 15 000 megatonnes per year). The modern Orange River in southern Africa pours *ca.* 200 megatonnes per year of sediment offshore onto a subsiding continental margin, which formed by stretching in the Cretaceous (approximately 130 million years ago) as Africa separated from South America. Seismic data from the Orange Delta reveal the history of sedimentation (figure 4). This delta has grown over the last 60 million years, forming a set of discrete seaward-dipping depositional sequences. Each sequence forms gradually with time as the river load is deposited on the subsiding shelf. In this way, large deltas grow or prograde out to sea. In front of the delta (i.e. downslope), deep-sea channels and submarine fans of sediment form. Discrete sequences are generated by temporal changes either in the locus of the river mouth, in the rate of sediment supply, or in the relative elevation of the land surface with respect to sea level. Changing patterns of sedimentation are thus recorded through geological time. Deposition is not steady-state: deltas as well as deep-sea submarine fans exhibit pulsing, and the challenge for Earth scientists is to determine how such pulses might be linked to vertical motions of the land surface, changes in sea level, climatic variations or other processes.

Ancient deltas and submarine fans from many locations are seen on seismic images. A good example of an ancient submarine fan complex is found in the North Sea Basin (figure 3*a*). This fan complex is approximately 55 million years old and appears as a series of sigmoidal reflections that prograde or build eastwards. Such depositional geometries demonstrate that rivers were transporting large volumes of sediment into the slowly subsiding North Sea Basin from an uplifted region to the west, encompassing Scotland.

In figure 5, a three-dimensional image of a submarine channel system of similar age and location is shown. Where the cube of data has been cut way, a large meandering submarine channel is clearly visible (figure 5*a*). It is imaged because sandy deposits within the channel have different acoustic velocities and densities compared with surrounding deep marine muds. The three horizontal slices are snapshots that show what the channel system looked like at different points in geological time. Note how a broad and linear set of channels evolved into a single well-established meandering channel within several hundred thousand years (compare parts *b* and *c* in figure 5). This channel system was transporting sediment from an emergent region to the west. Combined three-dimensional datasets of this quality can be used to estimate changes in solid flux of sediment through time.

5. Does the solid Earth pulse?

Between 62 and 54 million years ago, an area which includes the British Isles (*ca.* $3 \times 10^5\ km^2$) underwent rapid uplift and erosion. Substantial quantities of muds and sands were deposited in the North Sea Basin and surrounding regions. In 1766, Lavoisier noted that marine sedimentation was often strongly pulsed and attributed this pattern to the 'flux and reflux of the sea'. Modern subsurface imaging shows that submarine fan activity in the North Sea Basin waxed and waned with a periodicity of 1–2 million years. White & Lovell (1997) have suggested that the timing of these sediment pulses is linked to episodic surface uplift related to the injection of magma beneath the British Isles. The timespan of fan deposition and magmatic activity are very similar and the phase of greatest fan development coincides with the climax of magmatism between 61 and 58 million years ago (figure 6). The remnants of this magmatism can still be seen in western Scotland and in Northern Ireland, where lavas form the famous Giant's Causeway; its outpouring was related to activity of the Iceland plume, a long-lived convective upwelling of hot mantle at depth.

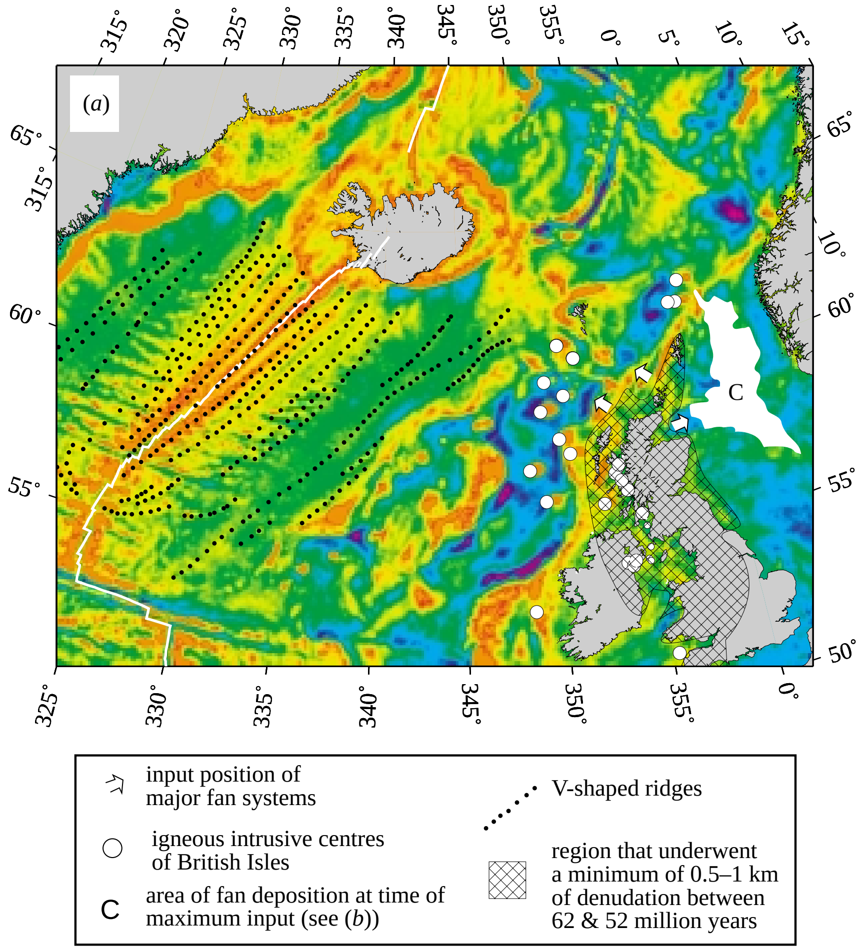

Figure 6. (*a*) Satellite-derived free-air gravity map of Sandwell & Smith (1992) for the North Atlantic Ocean (equal area projection). Warm colours indicate gravity highs and cold colours indicate gravity lows: gravity can be regarded as a proxy for bathymetry. The plate-spreading axis is indicated by a solid white line and the present-day mantle plume centre is in southern Iceland. Solid circles delineate prominent V-shaped ridges, which are symmetrical about the spreading axis and converge southwards. These ridges were generated when pulses of anomalously hot mantle upwelled beneath Iceland. The white circles around the British Isles are major igneous centres, and the shaded patch is a region that underwent uplift and erosion. Offshore deposits are shown as white irregular patches.

These inferences can be tested using independent, but less well-resolved, evidence for temporal fluctuations in plume activity over the last 60 million years. Prominent V-shaped ridges on the sea floor south of Iceland are generated by pulses of hotter mantle as they travel radially away from the centre of the plume (figure 6*a*). These pulses occur on a time-scale of several million years and probably reflect changes within the core of the plume. The link between mantle convection and sedimentation is unlikely to be straightforward. Nonetheless, a range of independent observations support the hypothesis that the existence of discrete pulses of ancient submarine fan deposition can be linked to convection.

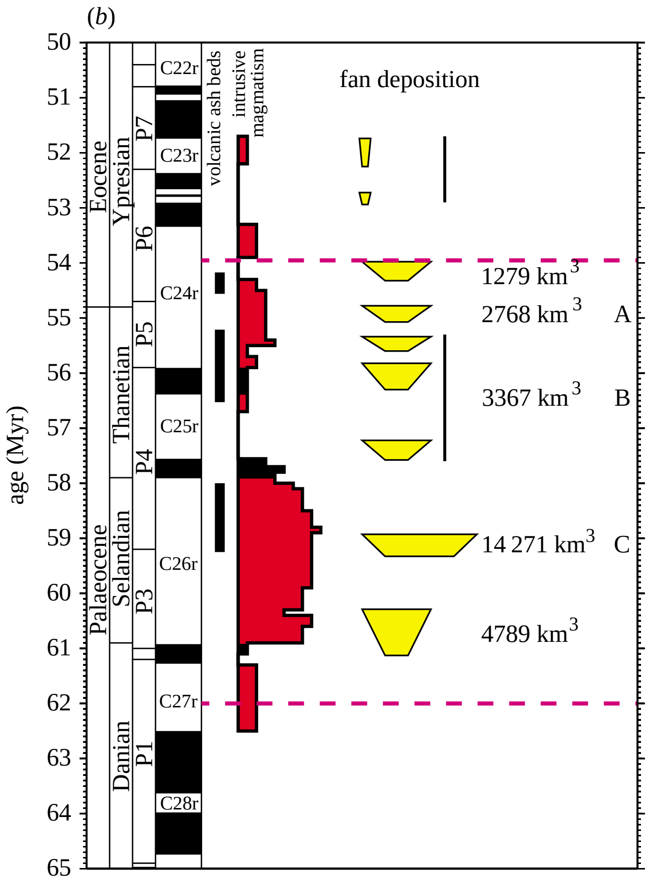

Figure 6. (*b*) A stratigraphic chart showing the temporal relationship between intrusive igneous activity, offshore volcanic ash beds, and submarine fan deposition in the North Sea (White & Lovell 1997). At the left-hand side, stage names, planktonic foraminiferal biostratigraphic zonation, and magnetostratigraphy are shown. A histogram of igneous activity gives the impression of range and the intensity of the magmatism. The wedges with solid circles are aggregated submarine fan deposits (A is shown in figure 5; B in figure 3). Horizontal dashed pink lines at 62 and 54 Myr mark the initiation of the Iceland plume and the start of seafloor spreading between Greenland and Europe, respectively. Total fan volume in the North Sea from 62–54 Myr is *ca.* 26 000 km^3 (*ca.* 6×10^{16} kg). By 54 Myr, submarine fan volumes are considerably smaller.

These ideas were developed in the North Atlantic region, where large amounts of two-dimensional and three-dimensional seismic data can be used to map submarine fan deposits in considerable detail. It is now opportune to carry out a similar analysis in other areas where both convective upwellings and downwellings occur. One such example is India, which rifted away from the Seychelle Islands 65 million years ago over the Réunion plume. Extensive magmatism occurred, forming the dramatic Deccan traps of Western India. Associated uplift and tilting triggered the erosion of large quantities of sediment, which were transported across India into basins off the east coast. Analysis of these sedimentary deposits could help to resolve otherwise inaccessible time-dependent details of the convecting mantle.

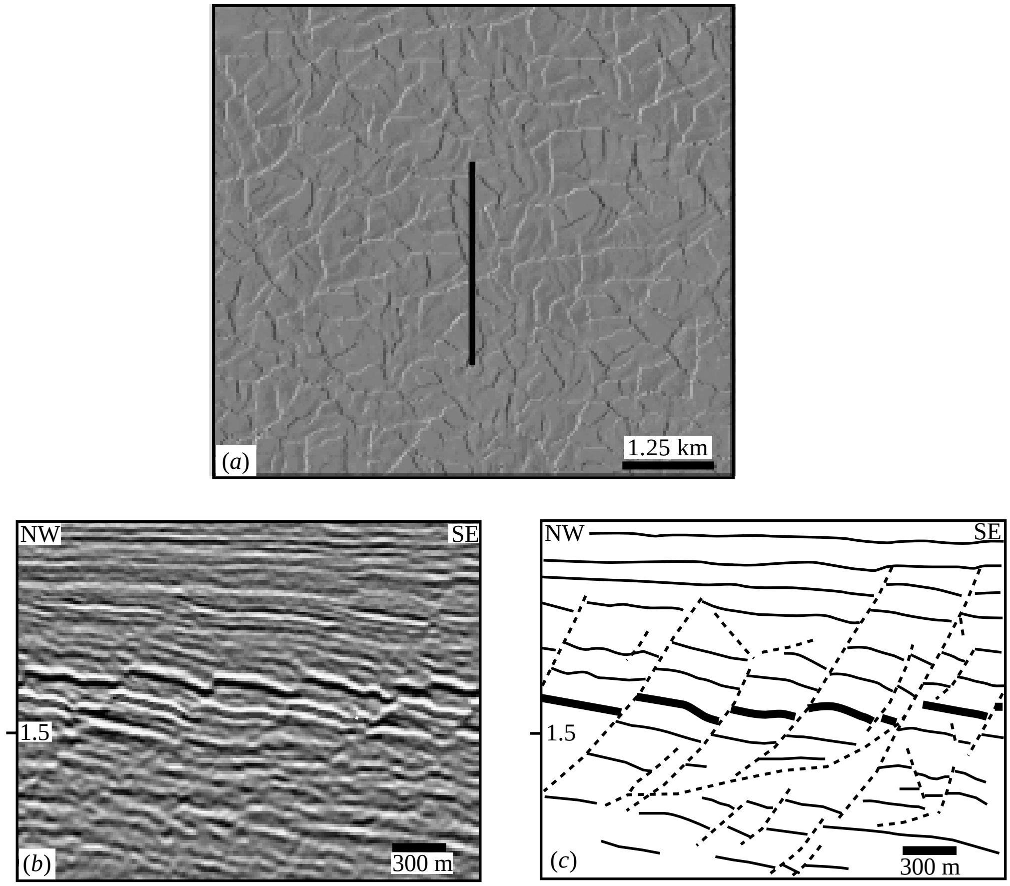

Figure 7. (*a*) A surface relief map from a cube of North Sea data made by interpreting a single stratigraphic surface throughout the three-dimensional seismic volume (approximately 1000 lines at 12.5 m spacing). The dip of the mapped surface was then calculated and illuminated by a light source shining from the NW, so that the polygonally faulted surface is thrown into relief. (*b*) A vertical cross-section that reveals the geometry of the polygonal faults. (*c*) A detailed interpretation of (*b*). Faults are shown as dashed lines; different stratigraphic layers are shown by thin black lines; the surface mapped in (*a*) is shown by a thick black line. Data courtesy of Fina & Chevron.

6. A closer look

(*a*) *Polygonal faults*

Three-dimensional seismic images have been instrumental in discovering a variety of unexpected features that are less easy to recognize in two dimensions. The most obvious examples are submarine channel systems, which are barely detectable in cross-section (figure 5). Recently, Cartwright & Lonergan (1996) have described an unusual and extensive network of faults that occur within mud-dominated strata over an area of *ca.* 150 000 km^2 in the North Sea (figure 7). In cross-section, these faults look like a small-scale version of the faults in figure 3. However, careful three-dimensional mapping has shown that these faults are organized in sets of polygons, rather like gigantic mud cracks. They were first discovered in the North Sea Basin and now similar networks are being found in other sedimentary basins worldwide.

The geometry of these faults suggests that the sedimentary succession has undergone a roughly equal amount of extension in all directions. However, this deformation cannot be caused by stretching of the crust and lithosphere since polygonal faulting is confined to individual sedimentary layers. Instead, the formation of these fault networks is attributed to the way in which water-bearing muds expel fluid during the process of compaction. This process is thought to be caused by the contracting of colloidal gels within the muds (Dewhurst *et al*. 1999). Mudrocks, because of very their low matrix permeabilities, are often considered a suitable lithology in which to bury toxic waste. However, the recent discovery of connected, regionally pervasive polygonal fault systems in thick mudrock sequences must question the assumption that fluids generally do not flow through mudrocks.

(*b*) *Fluids*

The acoustic impedance of a rock is the product of its acoustic velocity and density. When seismic energy is reflected from the boundary between two rock types, the amplitude of the reflected wave depends upon the acoustic impedances of the two rocks. Impedance depends on the mineralogical composition of a rock, on its porosity, and on the density and phase of the fluid contained within pore spaces. A typical sandstone has a porosity of 10–20%, and sharp changes in impedance can occur depending on whether the pore spaces are filled with water, oil or gas. Accordingly, the measured amplitude of a reflection can be used, under favourable circumstances, to identify the pore fluids.

Figure 8 illustrates how amplitude modelling can help in producing hydrocarbons. When oil and gas are extracted, encroaching waters gradually alter the distribution of the remaining hydrocarbons. Successful economic management of a producing field depends upon the ability to predict the changes in such fluid flow. Repeated three-dimensional seismic surveys (known as '4D' or 'time-lapse' surveys) help to monitor the movement of different pore fluids through the subsurface and to discover where remaining pockets of hydrocarbons lie.

7. The future

Although three-dimensional surveying is now used routinely by the hydrocarbon industry, its considerable potential has yet to be fully exploited by other scientists. Thanks to the enlightened generosity of the hydrocarbon industry, large amounts of three-dimensional imagery from sedimentary basins and continental margins will keep many Earth scientists busy for a long time. In this article, we propose one line of enquiry that exploits existing three-dimensional seismic databanks. There are many other important and tractable problems that require three-dimensional seismic surveying.

In the oceans, the most obvious target is the mid-oceanic ridge system, where tectonic plates spread apart and grow, generating large quantities of magma that form new oceanic crust. Although a considerable number of two-dimensional seismic reflection surveys have shown that melt can be imaged at several kilometres depth

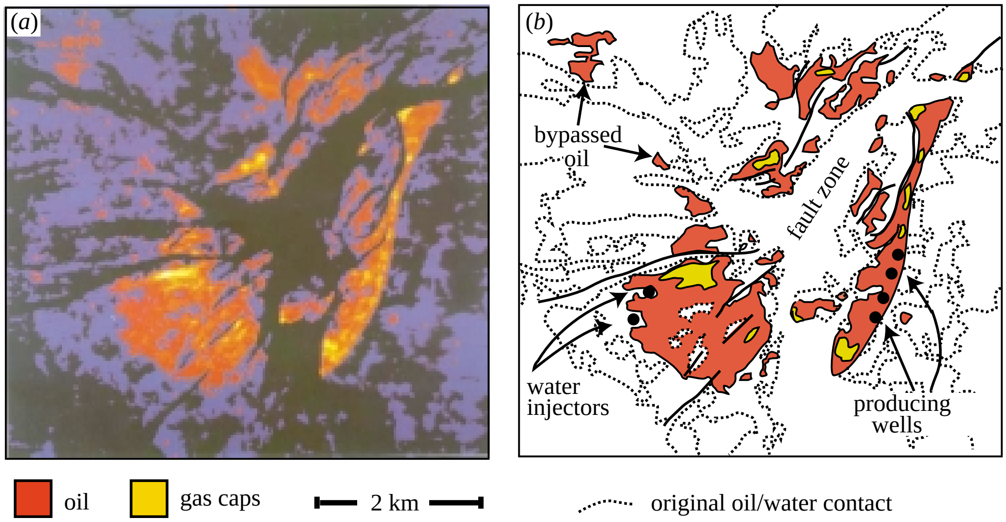

Figure 8. (*a*) A seismic amplitude map from a three-dimensional survey of the producing oil field in the Gulf of Mexico. By carefully calibrating the amplitude of recorded seismic waves, Shell geologists discriminated between sediments whose pore spaces contain water (blue), oil (red) or gas (yellow). The extent of the original oil field is gauged from the distribution of oil patches left behind by encroaching waters. Several gas caps are clearly visible, including those that develop at the loci of producing wells. The entire field is dissected by both large and small faults. Data courtesy of Shell Oil.

beneath fast-spreading ridges, we have little understanding of the three-dimensional geometry of these melt bodies. The first three-dimensional survey to target a mid-oceanic ridge was shot during September–October 1997 by an Anglo-American group (Singh *et al*. 1999). Data were acquired over a $20 \times 23\,\mathrm{km}^2$ grid on the East Pacific Rise. These data are now being analysed jointly at Cambridge University and Scripps Institute of Oceanography.

Future targets include active volcanoes located either onshore or offshore, active normal faulting in regions that are undergoing rapid lithospheric stretching, and the accretionary prisms that develop where one plate is subducting beneath another. In each case, there exists the exciting prospect of four-dimensional surveying following eruptions or earthquakes. Such data would undoubtedly help to improve our understanding of the dynamics that govern these fundamental processes.

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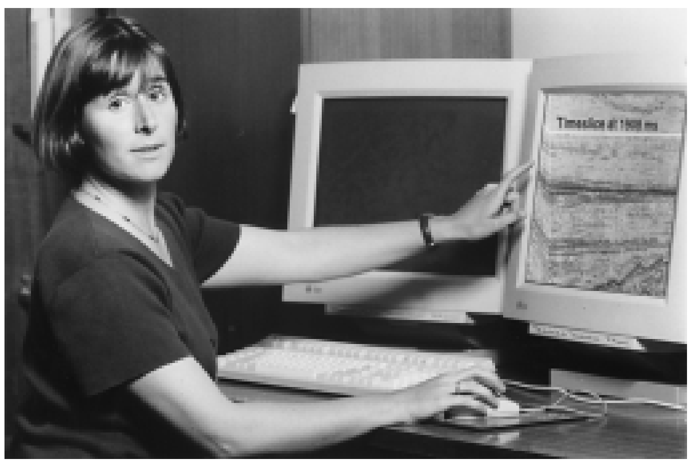
Lidia Lonergan graduated from Trinity College, Dublin, in 1988 with a first class honours degree in geology. From 1988 to 1991 she studied for a DPhil at Oxford, supervised by John Dewey and John Platt. She then joined Shell Research in Holland and worked in a team developing basin modelling software. Since late 1994 she has been at Imperial College, first as a Fina Lecturer and since 1996 as a Royal Society University Research Fellow. At Imperial College she has a taken a leading role in building up the three-dimensional seismic interpretation facility and manages the interpretation laboratory. Aged 32, her main research interests are tectonics and using three-dimensional seismic datasets to address fundamental scientific problems within the Earth sciences.



N. White

Nicky White has a first class honours degree in geology from Trinity College, Dublin. From 1984 to 1988, he carried out a PhD in geophysics at Cambridge, supervised by Drum Matthews and Dan McKenzie. The next two years were spent working for the British Institutes Reflection Profiling Syndicate (BIRPS). Since 1990, he has lectured at Cambridge, where he is now an Assistant Director of Research. His research interests are focused on extracting quantitative information about Earth processes from sedimentary basins worldwide. Many of the data he works on have been acquired by the petroleum industry, with which he has close and fruitful links. Aged 37, he runs a research group of 12 PhD students.