EXPLORING FOR FAN AND DELTA SANDSTONES IN THE OFFSHORE FALKLANDS BASINS

P. Richards*[1], I. Duncan[2], C. Phipps[2], G. Pickering[3,4], J. Grzywacz[3], R. Hoult[1,5] and J. Merritt[1]

Four basins surround the Falkland Islands, but only the North Falkland Basin has been drilled; six wells were drilled there in 1998. Although all six wells encountered good quality sandstones, none of them targeted the basin margins, on what are now thought to be the optimum migration pathways associated with the basin's thick lacustrine source rocks. Subsequently, a 3D seismic survey acquired in 2004 was designed to identify potential basin-margin -derived sandstones entering the basin along transfer zones. From this survey, a number of basin-margin -attached fans have been identified; these prograded into lacustrine waters of varying depths. These Early Cretaceous alluvial/fan delta/deep-lacustrine fan systems are interpreted to provide excellent potential reservoir facies as they are intimately associated with thick, mature source rocks. They will provide the focus for the next planned phase of exploration in the North Falkland Basin.

A phase of drilling is also planned for the basins to the south of the Islands, where large deltaic and fan systems, slightly younger than those imaged in the North Falkland Basin, are seen on seismic to prograde from the same Palaeozoic hinterland that produced the older, North Falkland Basin fans.

This paper attempts to show how sedimentary models derived from targeted seismic programmes following initial exploration can be utilised to plan and improve new drilling campaigns in a frontier basin. It presents an analysis of sediment dispersal patterns in basins of marine and lacustrine origin linked to a single hinterland area, and highlights the nature of the relationship between relay ramp/transfer zone development and sediment dispersal patterns in the sub-surface.

INTRODUCTION

The Falkland Islands are surrounded by four Mesozoic-Cenozoic basins (Fig. 1). The Malvinas, South Falkland and Falkland Plateau Basins lie to the west, south and east of the Islands, respectively. They have a probable Devonian to Permian economic basement, and are predominantly infilled by Middle Jurassic to Cenozoic rocks of marine origin (Richards and Fannin, 1994; Richards *et al*., 1996 a and b; Platt and Phillip, 1995). Minor Early to mid-Jurassic volcanics and some intrusives are interbedded with the sedimentary rocks in the Malvinas Basin and South Falkland Basin. None of the southern basins have been drilled within Falklands waters, and the nearest wells are located to the west, in the middle of the Malvinas Basin, or several hundred kilometres to the east, where three DSDP boreholes were drilled on a bathymetric feature known as the Maurice Ewing Bank.

The North Falkland Basin (Fig.1) has a predominantly non-marine ?Jurassic to mid-Cretaceous infill above Devonian basement, overlain by a progressively more marine succession of sedimentary rocks of Late Cretaceous to Recent age

[1] British Geological Survey, West Mains Rd, Edinburgh, EH9 3LA.
[2] Desire Petroleum plc, Mathon Court, Mathon, Malvern, Worcestershire.
[3] RPS Energy, Goldsworth House, Denton Way, Goldsworth Park, Woking.
[4] Now at: Granby Oil and Gas plc, Antholin House, 71 Queen Street, London.
[5] Now at: GETECH, University of Leeds, Leeds, West Yorkshire.

*author for correspondence, email: pcr@bgs.ac.uk

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(Richards and Hillier, 2000 a). The non-marine ?Jurassic to Middle Cretaceous succession contains a thick, partially mature lacustrine claystone source rock of ?Tithonian to Aptian age. A drilling campaign of six wells in 1998 proved the presence of several intervals of high-quality reservoir sandstones, particularly in the post-rift succession above the lacustrine claystones (Richards and Hillier, 2000 a and b).

The 1998 drilling campaign was in general a technical success but not a commercial success: most of the post-rift reservoir levels encountered above the mature oil source (Fig. 2) were under-charged with respect to oil, because the topmost parts of the source rock tends to act as a regional seal (Richards and Hillier, 2000 b). No attempt was made during the 1998 drilling to target potential basin-margin sandstones (Fig. 2), on what are now thought to be the optimal routes for oil migration from the thick lacustrine claystones (Richards and Hillier, 2000 b).

PREVIOUS WORK ON FANS IN THE FALKLANDS BASINS

Based on 1995 exploration 2D seismic, Platt and Phillip (1995) and Richards *et al*. (1996 a and b) interpreted the presence of large deltaic and/or lowstand fan bodies along the western margin of the Falkland Plateau Basin. These were thought to have prograded into the basin towards the SE, having been eroded from a Devonian and/or Permian hinterland of sedimentary rocks on the Falkland Platform in the vicinity of the Islands. Given the generally very clean nature of the sands currently found along Falklands beaches, it was assumed that these fan bodies would, having presumably eroded a similar landmass, be rich in quartz-dominated sand.

The 1995 vintage 2D seismic data on which the Falkland Plateau Basin deltas and/or fans were identified were reprocessed in 2004, facilitating a clearer interpretation of these features. Also, exploration 2D seismic data acquired over the eastern margin of the Malvinas Basin in 1995 (and subsequently reprocessed in 1997) have allowed the identification of the previously unreported large delta/fan systems prograding off the Falklands Platform towards the SW.

No major fan sandstones have been reported previously from the margins of the North Falkland Basin, although Richards and Hillier (2000 a) described a basin-centre, lowstand attached-fan developed in front of a northerly-derived axial deltaic system within the Early Cretaceous lacustrine, early post-rift section of the basin. This fan, and the associated axial delta from which it was derived, prograded from a hinterland to the north of the Falklands, and did not erode the predominantly sandy hinterland seen onshore in the Islands. However, Richards and Hillier (2000 b) also alluded to the development of both lacustrine fan and lacustrine delta sandstones derived from the adjacent Falklands Platform. They noted that such sandbodies would be stratigraphically adjacent to mature oil source rocks, and therefore lie on optimum migration pathways within the basin (Fig. 2). Furthermore, they noted that such fans were difficult to identify on the basis of existing seismic data, and that they might be significantly more extensive than was thought at the time.

FANS IN THE NORTH FALKLAND BASIN

Following on from the conclusion presented by Richards and Hillier (2000 b), that sandstones lying stratigraphically above the main lacustrine source rocks in the North Falkland Basin are under-charged where penetrated in the central parts of the basin, these authors suggested that future targets should include basin-margin -derived sandstones. These are laterally equivalent to the mature source rocks and are below the regional seal provided by the upper part of the source interval. However, such fan/fan delta sands were not well imaged on seismic data, and were therefore difficult to locate, particularly along the eastern margin of the North Falkland Basin. Subsequently, further analyses of the 1998 North Falkland Basin drilling campaign conducted in-house by BGS and Desire Petroleum highlighted the potential for syn- to early post-rift sands to have entered the lacustrine basin along basin-margin offsets, transfer zones and relay ramps as described below, thus further focussing interest on these zones as sites for future exploration activity.

The structural framework for fan sand development in the North Falkland Basin

Richards *et al*. (1996 a and b) and Richards and Fannin (1997) demonstrated that the main N-S structural grain of the North Falkland Basin, produced by E-W oriented Mesozoic extension, comprises normal faults with a segment length of up to about 25 km, offset by right-lateral displacements of up to 9 km. These transfer zone offsets occur along NW-SE oriented faults, which are best imaged on seismic data from the southernmost parts of the North Falkland Basin (Fig. 1). The transfer zones formed when the pre-existing NW-SE structural grain, which was probably initiated as a series of thrust sheets during Palaeozoic compression, was initially re-activated and extended under east-west directed extensional stress during the Jurassic (Richards et. al., 1996 a and b; Richards and Fannin, 1997).

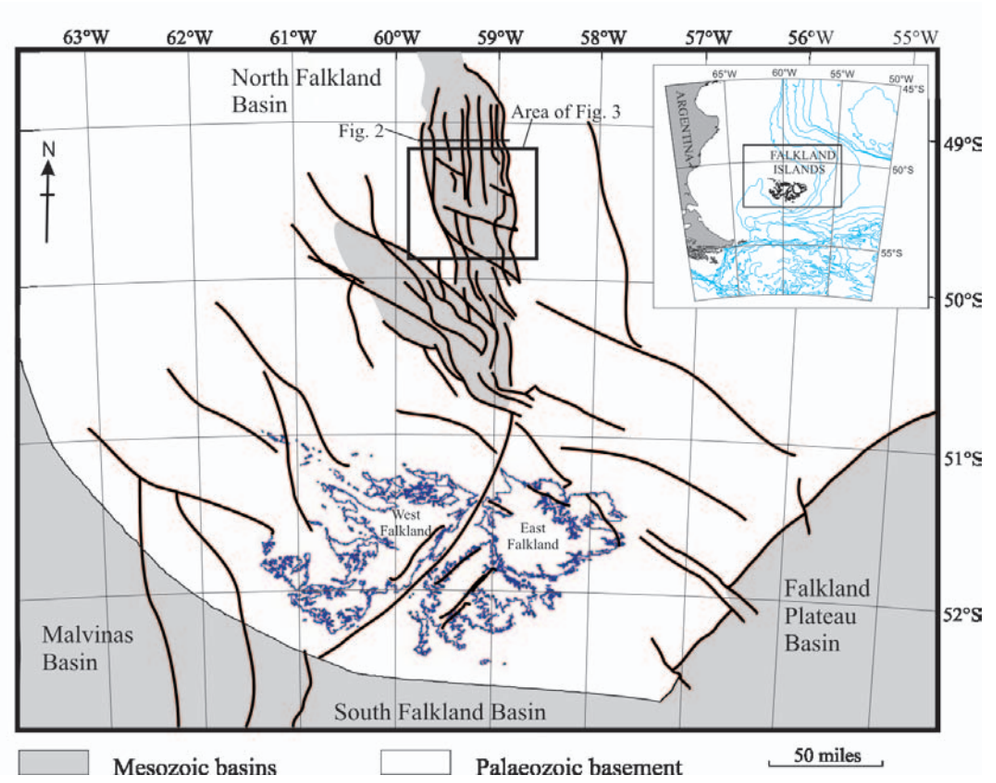

Fig. 1. Outline map of the Falklands basins and the controlling fault trends. Jurassic-Cretaceous extensional faults in the North Falkland Basin are oriented north-south. The NW-SE oriented lineaments reflect an underlying and reactivated Palaeozoic structural grain. Box shows the location of Fig. 3. The Mesozoic basins (grey shading) are surrounded by a Palaeozoic platform (white).

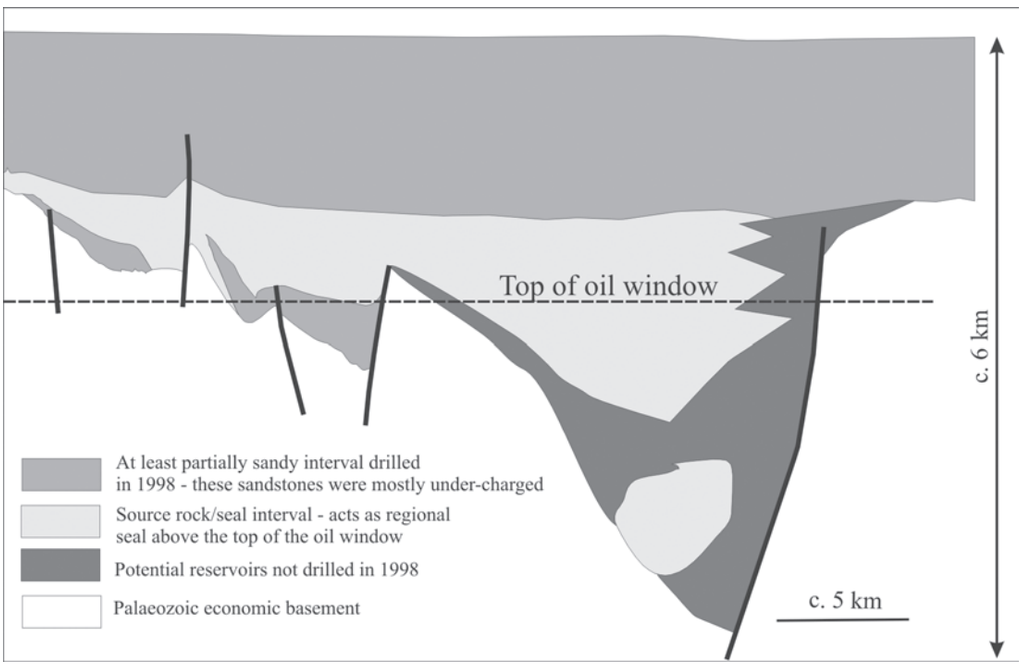

Fig. 2. Schematic W-E cross-section across the North Falkland Basin, illustrating the under-charged sands above the regional source-seal couplet, and untested marginal sands (darkest shading). (See Fig. 1 for approximate profile location).

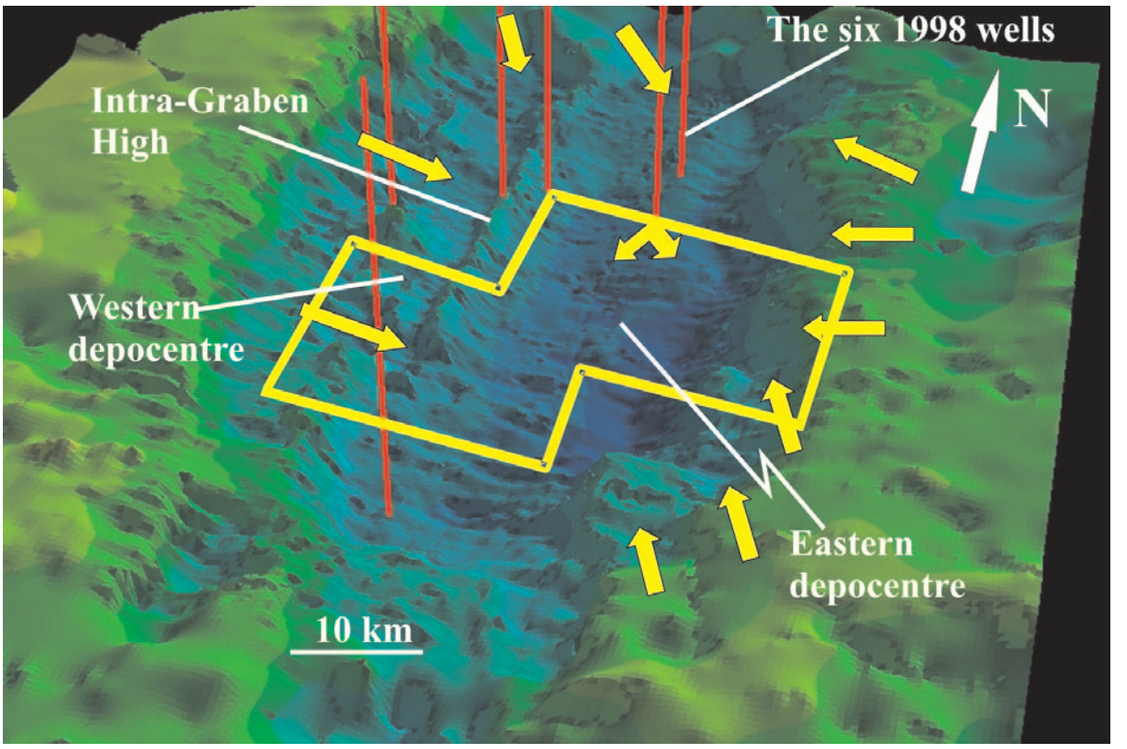

Fig. 3. Three-dimensional representation (constructed in Arc 3D) of the top of the syn-rift succession in the central part of the North Falkland Basin, based on 1997 and older 2D seismic data, showing fault offsets, relay ramps and transfer zones, which are the predicted sand entry points to the basin (yellow arrows) and the new 3D survey area (yellow box). The positions of the 1998 wells are shown as red lines. See Fig. 1 for location.

As a part of their review of the basin, and building on the work of Richards and Hillier (2000 a and b), the present authors utilised three-dimensional images of the North Falkland Basin's 2D seismic data, created using ArcGIS 3D modelling software, to produce visualisations of the basin margin and intra-basinal fault offsets, transfer zones and associated relay ramps. These 3D block images facilitated the prediction (using models such as those developed by Leeder and Gawthorpe, 1987; Gawthorpe and Hurst, 1993; Eliet and Gawthorpe, 1995; and Trudgill, 2002) of the probable position of potential sand entry points into the basin along the transfer zones, across footwall uplift zones and down hangingwall slopes. One of these 3D visualisations (Fig. 3), at the stratigraphic level of the top of the syn-rift succession, highlighted the fact that the most likely sand entry points to the basin were probably laterally adjacent to the structurally deepest parts of the lacustrine basin. These sand entry points are therefore the most likely sites to produce the inter-fingering of mature source rock intervals and reservoir sandstone packages along short and simple migration pathways.

In the central parts of the North Falkland Basin, where the NW-SE transfer zones offset the so-called Intra-Grabenal High (terminology of Richards and Fannin, 1997) separating the eastern and western depocentres of the basin, there is no obvious development of relay ramps, but the transfer offsets (Fig. 3) were still considered to be major sediment entry points from the west into the eastern depocentre. Indeed, post-drilling mapping had identified the development of contour bulges along these transfer zones at several stratigraphic levels, although no three-way dip closure could be mapped on the basis of the existing 2D seismic data, and therefore no discernible targets could be identified at those locations to support future drilling plans at that time.

A new 3D seismic survey covering approximately 800 km^2 was therefore planned and initiated by Desire Petroleum to help identify the location of basin-margin- derived sandstones of different provenance to the northerly-derived axial deltas and younger post-rift reservoirs that had been drilled previously in the centre of basin. This 3D survey (Fig. 3) was acquired and processed in 2004, and its interpretation has facilitated the mapping of numerous fan bodies associated with the thick lacustrine source rock.

Direct hydrocarbon indicators and the methodology of fan identification

The new 3D survey was acquired using a tuned airgun array with an output of 3450 cubic inches, and six streamers each of 5,000 m length (towed at 10 m

depth), with a group spacing of 12.5 m and a cross-line CDP spacing of 25 m. The survey was shot in an east-west direction, in two overlapping boxes to produce maximum coverage of the previously recognised transfer zone elements (Fig. 3). The data were processed in the UK by the acquisition contractor (Fugro-Robertson), and post-stack time-migrated sections in SEG-Y format were produced for loading into workstations.

Initial structural interpretation of the 3D survey indicated that, as predicted, there were several three- or four-way dip closures in the area of the survey: these have been mapped and evaluated as potential drill sites for the next phases of drilling in the North Falkland Basin. However, the main focus of this interpretation work was aimed at evaluating the potential for the development of fan and margin-attached sandstones within the syn-rift to earliest post-rift succession. Such sandstone bodies are inter-bedded with the mature part of the main lacustrine source rock beneath the regional seal at approximately 2,800 m below sea level: these sands were not targeted by any of the six wells drilled in 1998. Although several such potential sandstone bodies had been predicted to be located along, or associated with, the relay ramps and transfer zones previously identified, the new 3D seismic survey provided the first opportunity to map such features.

Given the age and maturity of the anticipated Early Cretaceous reservoirs, obvious direct hydrocarbon indicators (DHIs) would not generally be expected: such features are more commonly observed from Cenozoic sediments. However, during routine mapping of the 3D dataset, a number of relatively bright seismic anomalies and more-or-less diffuse flat spots were identified as possible DHIs (Fig. 4). Some seismically opaque zones were seen beneath the regional seal, which may be indicative of gas.

Gas release can lead to the development of pock-marks at or near the surface, and several zones of pock-marks have been identified on the present dataset (Fig. 4a), supporting the hypothesis of vertical gas escape within the central parts of the basin. Several clusters of these observed gas-escape generated pock-marks lie vertically above a diffuse flat spot identified at 2500 ms TWT (two-way travel time), possibly suggesting that they originated by gas escape from the margins of a potential hydrocarbon accumulation at that level. This areally extensive, diffuse flat spot (Fig. 4b) extends over some 10 km^2, and appears to mask truncations of strata within the syn-rift package. It occurs just beneath a major unconformity near the western edge of the eastern depocentre, where syn-rift sedimentary rocks onlap the southern end of the Intra-Grabenal High. The flat spot is discordant with the contours drawn on the truncation surface immediately above it: a very similar relationship is observed in oilfields such as *Central Brae* in the South Viking Graben of the North Sea, where the oil-water contact is discordant with the structural contours (Turner and Allen, 1991).

Other flat spots recorded on the 3D survey are seen in narrow, linear zones, and are associated with convex-up patterns of reflectors above them (Fig. 4c). These are imaged on both sides of the basin, and are interpreted to represent possible hydrocarbon-water contacts within sandstones occupying incised valley feeder channels to the fan systems developed within the basin; these are described below (in the section on hinterlands and fan composition).

The fan sandstones interpreted here present as a series of zones of anomalously high seismic reflection amplitude. Amplitude extraction mapping using the "StratAmp" facility available from Landmark software was conducted on a large number of interpreted horizons associated with visual amplitude anomalies, in order to attempt to map the distributions of the anomalies. These "StratAmp" extractions were made variously using horizons with windows of up to 60 ms TWT above and below the interpreted horizons, either on the basis of an RMS amplitude value and/or of a maximum positive amplitude value. The resultant areal distributions were plotted as colour displays; polygons were drawn around each mapped anomaly, and all the resultant polygons were then input into an ArcGIS system running a complete play-fairway model of the North Falkland Basin. This facilitated the simultaneous display of overlapping and stratigraphically separate fan anomalies, together with the locations of potential feeder channels, transfer zones, source kitchen areas, etc.

FAN COMPOSITION AND THE NATURE OF THE HINTERLAND

No in-depth AVO analyses of the "StratAmp" anomalies has been conducted to determine the probable lithological nature of the fans. This is because there are no unambiguous ways of creating properly-constrained seismic ties back to any of the six wells in the basin. Although it remains a theoretical possibility that the "StratAmp" features could represent features other than sandstone bodies (such as carbonate stringers or lava flows), a reasonable judgement has been exercised in interpreting them to be sand-dominated fans on the basis of: (a) their fan-like geometry and morphology; (b) the stratigraphic and geographic link of the fans to hinterland deltas; (c) the link between the fans and the narrow, incised valley features that provide feeder channel entry points into the basin; and, (d) the fact that these feeder-points exhibit compactional drape indicative of sand-

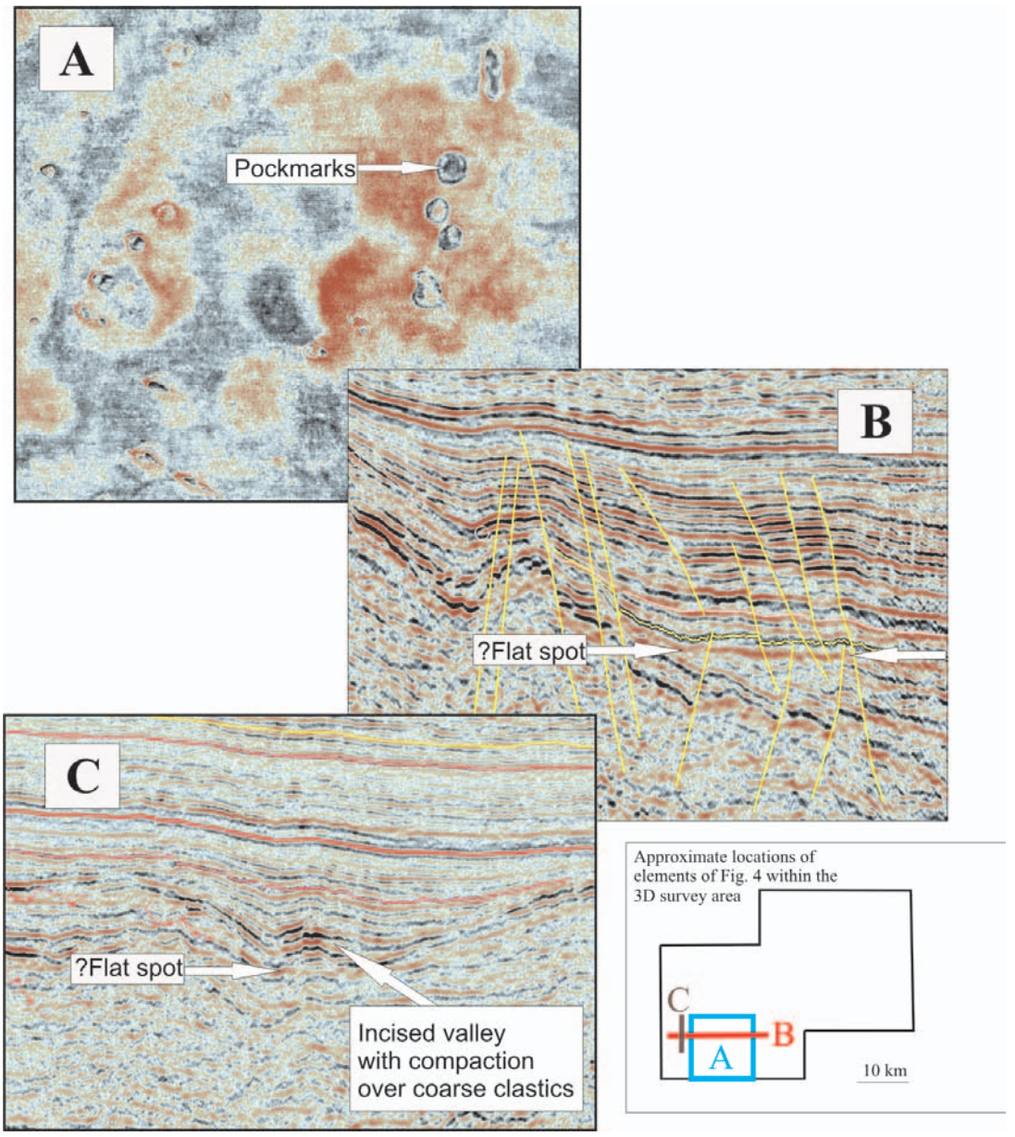

Fig. 4. Seismic panels from the new 3D dataset in the North Falkland Basin, showing: (a) horizontal slice illustrating pock-marks at approximately 650 ms TWT; (b) flat spot at 2500 ms TWT in the Liz fan area; (c) flat spot at the base of convex-up channel fill sandstones within the feeder to the Liz fan.

plugging. These points of evidence are discussed in turn below.

Fan-like geometry and morphology

The geometry and stratigraphic position of the individual fans is discussed in detail in the sections below on the nature of the fans on the eastern and western margins of the depocentre. However, it is worth noting here that they generally have a classic fan morphology. While fan morphology alone does not confirm the sandy composition of the fans, the "StratAmp" anomalies clearly point to some form of contrast in physical properties between the anomalies and the background lacustrine sediments, which Richards and Hillier (2000 a) have shown to be dominated by claystones. The amplitude anomalies are therefore interpreted as comprising coarser clastic material compared to the background claystones. The fans are interpreted to be composed predominantly of probably sand-grade material.

The link between the fans and feeder channels with compactional drapes

Several of the fans (described below) are attached to linear features interpreted as narrow, incised feeder channel systems that are clearly imaged on seismic sections. The Liz fan, for example, displays a very clear E-W oriented feeder zone (Fig. 4c) from the west. This feeder channel is up to approximately 1 km wide when imaged on StratAmp displays. It is

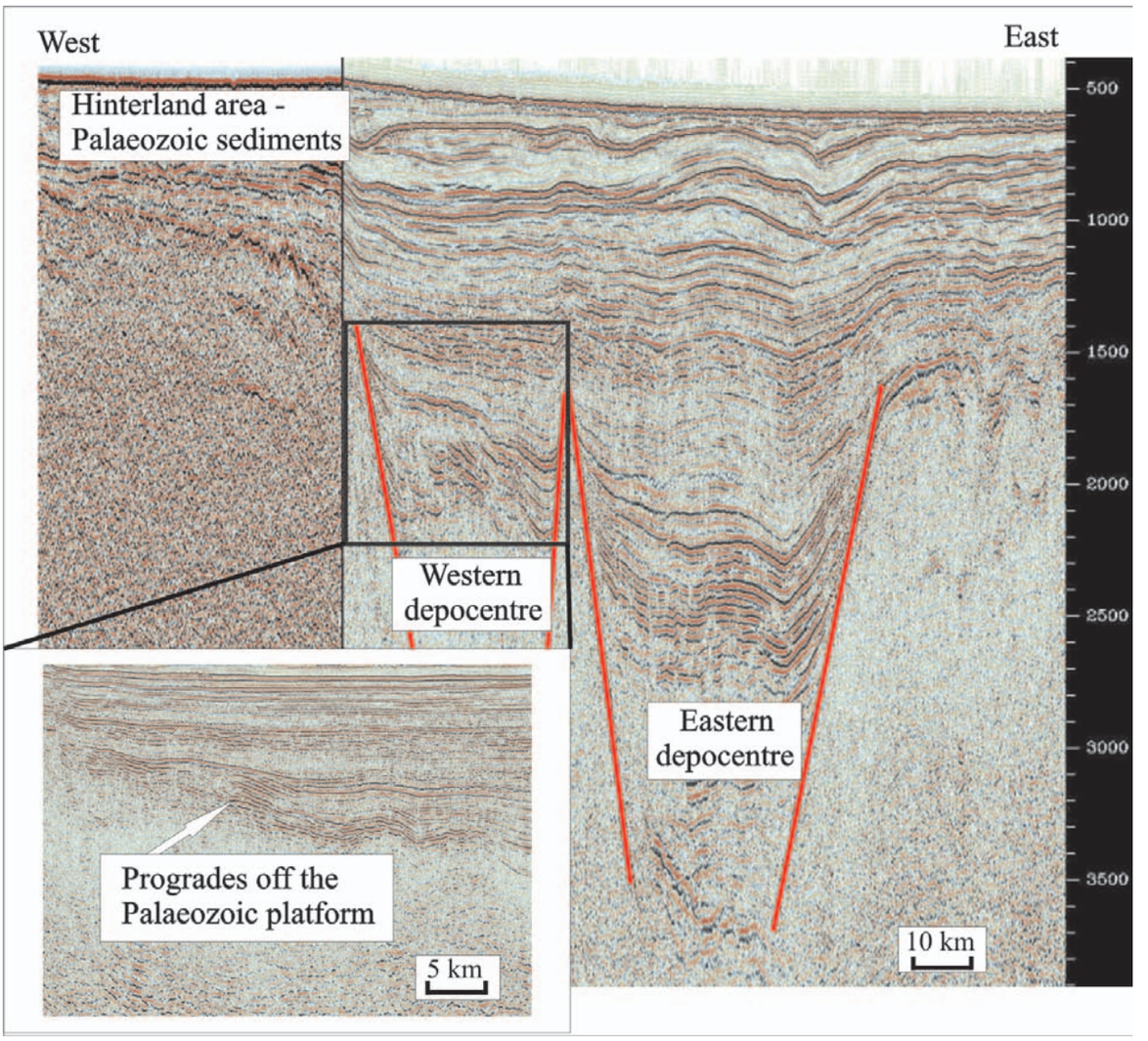

Fig. 5. West-east composite seismic section across the North Falkland Basin, illustrating the platform area that forms the hinterland for the fans (vertical scale is in ms TWT). The inset box shows detail of an Early Cretaceous delta complex prograding off the platform into the western depocentre of the North Falkland Basin.

characterised by an erosional hollow, infilled by high amplitude, convex-upwards reflectors, which are interpreted to represent compaction over a sandstone infill. This is a significant channel system, and compares for example with the lowstand incised valleys in the Kenilworth Member of the Cretaceous Blackhawk Formation of the Book Cliffs (SW Utah, USA) described by Taylor and Lovell (1995).

The stratigraphic and geographic link to hinterland deltas

Another factor that suggests that the fans are likely to be dominated by coarse clastic materials is that they appear to drain a probable Palaeozoic platform area on both the western and eastern margins of the North Falkland Basin (Figs.1 and 5). The platform is likely to comprise materials similar to those that make up the bulk of the landmass of the Falkland Islands themselves, which are dominated, at least in their northern parts, by Siluro-Devonian quartzites, sandstones and more minor mudstones.

The incised valley feeder channels that link the fans with the hinterland area can be mapped, particularly at the western margin of the eastern depocentre of the North Falkland Basin, as being stratigraphically sub-jacent to an early post-rift delta of probable Valanginian to Hauterivian age that appears to prograde from west to east into the western depocentre lake basin. This progrades from a hinterland composed of the surrounding Falklands Plateau Palaeozoic sedimentary rocks. The delta is similar to a number of partially-linked and

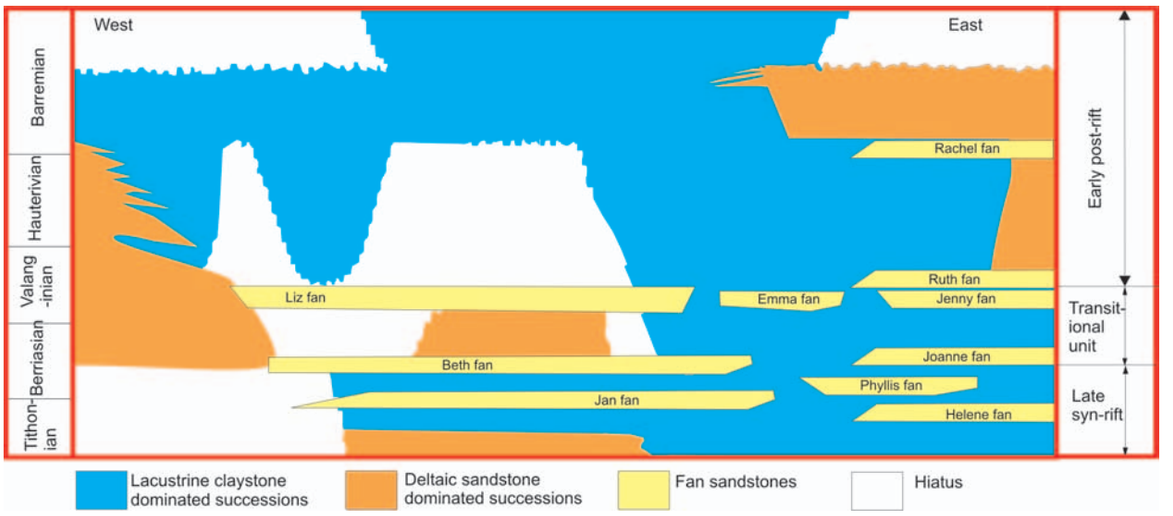

Fig. 6. Sequence stratigraphic chart for the Late Jurassic and Early Cretaceous in the central North Falkland Basin, illustrating the stratigraphic position of the various fans and deltas. See Richards and Hillier (2000a) for a more comprehensive sequence stratigraphic framework for the basin.

overlapping sand bodies mapped on 2D seismic data in the western depocentre. These deltas are stratigraphically equivalent to the older parts of the main axial delta which infilled the lake from the north during the early post-rift highstand (see Richards and Hillier 2000 a).

FANS DERIVED FROM THE WESTERN BASIN MARGIN OF THE EASTERN DEPOCENTRE

Based on the location of north-south trending fault offsets and the positions of associated transfer zones, fan sandstones were predicted to occur along at least three major potential entry points into the western margin of the eastern depocentre of the North Falkland Basin (Figs. 3 and 4). Only the southernmost of these three locations was covered by the new 3D survey (Fig. 3); this was a result of cost constraints rather than qualitative assessment that the other zones were of more limited potential in terms of sandstone development.

The southernmost of the three potential fan sites lies at the southern end of the Intra-Grabenal High separating the western and eastern depocentres of the basin (Fig. 3). The high is offset dextrally, and the transfer fault continues SE across the basin to form, at the eastern margin, a hard-linked relay ramp at an eastern margin offset (Fig. 3). To the west of the Intra-Grabenal High, in the western depocentre, an early post-rift delta (described above) has been interpreted to have prograded, from the surrounding Falklands Plateau, into the basin during the latter stages of lake development.

A series of seismic amplitude anomalies have been identified as possible fan bodies at the eastern extremity of, and stratigraphically either just beneath or at the base of, the westerly-derived delta. These may represent a series of lowstand sandbodies that prograded into the lacustrine basin before development of the delta, with sand introduced into the basin along deep, incised valleys cut into the margins of the eastern depocentre. Indeed, as noted above, when viewed on N-S oriented lines across the new 3D dataset, incised valley cuts at this stratigraphic level are seen to have a convex-upwards pattern of reflectors above them (Fig. 4c), possibly produced by differential compaction over a sandstone infill. These channels are connected to fans which lie stratigraphically within the late syn-rift and syn- to post-rift transitional zone intervals, spanning the late Tithonian to Valanginian (Fig. 6), and therefore formed at around the time that the basin was undergoing a major change in tectonism (see Richards and Hillier, 2000 a). Hinterland areas may have had their greatest relief at this time, before peneplanation of uplifted rift margin areas during the remainder of the post-rift phase.

Three separate fan bodies (Fig. 7) have been identified along the western margin of the eastern depocentre on the basis of positive amplitude anomalies mapped out as “StratAmp” features: two of the three fans are described below, while the third is placed in its stratigraphic and structural context. The fans are informally termed Jan, Beth and Liz. Jan, which is the oldest (?Tithonian - Berriasian), is located where late syn-rift strata onlap the western margin of the eastern depocentre; Beth (described below) is of

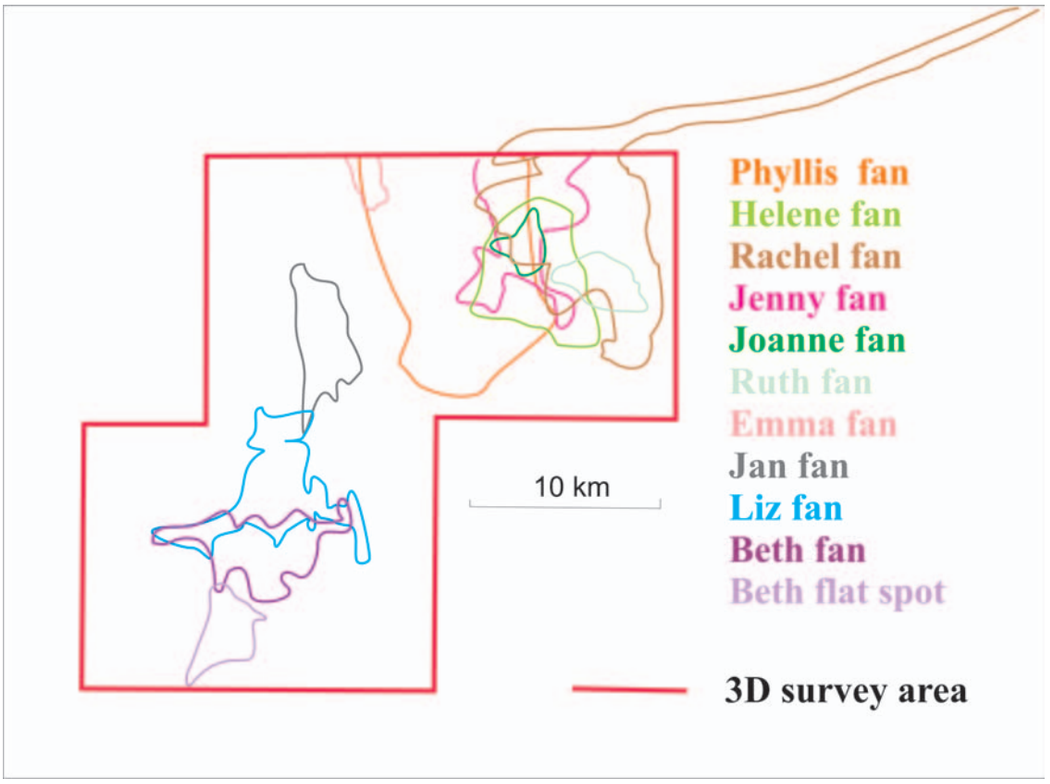

Fig. 7. Map of all the overlapping fan bodies identified on the new 3D dataset in the North Falkland Basin.

?Berriasian age, and is located at the very top of the late syn-rift succession; and Liz (described below) is of ?Valanginian age and is located within the transitional zone between late syn-rift and post-rift successions (Fig. 6). All three fans probably originate from a single point-source channel oriented along the transfer zone defining the southern end of the main part of the Intra-Grabenal High, and all three lie basinwards of the westerly-derived delta that infills the early post-rift phase of the western depocentre.

The Liz fan is the biggest of the western margin fans in terms of areal extent (Fig. 7), and maps out with a distinctive "StratAmp" display (Fig. 8). It displays a clear E-W oriented feeder channel (Fig. 8) from the west, approximately 1 km wide. The fan covers an area of approximately 31 km^2, and is compartmentalised by a number of NNW-SSE faults,which may segment and isolate reservoir zones. Seismic amplitudes vary across the fan (Fig. 8), probably in response to variations in sandstone thickness. The Liz fan forms a potential stratigraphic trap, with closure formed by lateral pinchout coupled with up-dip faulting which vertically offsets the fan from the feeder channel. This prospect will probably be drilled as the first target in the next phase of North Falkland Basin exploration.

The Beth fan is the most southerly, and the smallest, of the three western margin fans (Fig. 7). Although less distinctive than the Liz fan, it has a "classical" fan shape in plan view (Fig. 9), and originates from a point-source location shared by the slightly younger Liz fan (Fig. 7). The Beth fan is the only one of the three fans identified on the western margin of the eastern depocentre that has a three-way, fault-bounded structural dip closure associated with it.

FANS DERIVED FROM THE EASTERN BASIN MARGIN OF THE EASTERN DEPOCENTRE

Fan sands were predicted by Richards and Hillier (2000 a) to occur at several entry points along the eastern margin of the North Falkland Basin, both along relay ramps and transfer zones (Fig. 3). Two relatively minor relays and transfer zones along the eastern margin were covered by the new 3D survey (Fig. 3). Other transfer zones lie along the basin margin outside the new 3D coverage, providing significant further potential for locating fan sandstones elsewhere along the basin margin.

Unlike the western part of the basin, where a deltaic system can be linked to incised valley channels feeding the three fan sands described above, no deltaic successions have been observed directly to the east of the fans along the eastern margin of the basin.

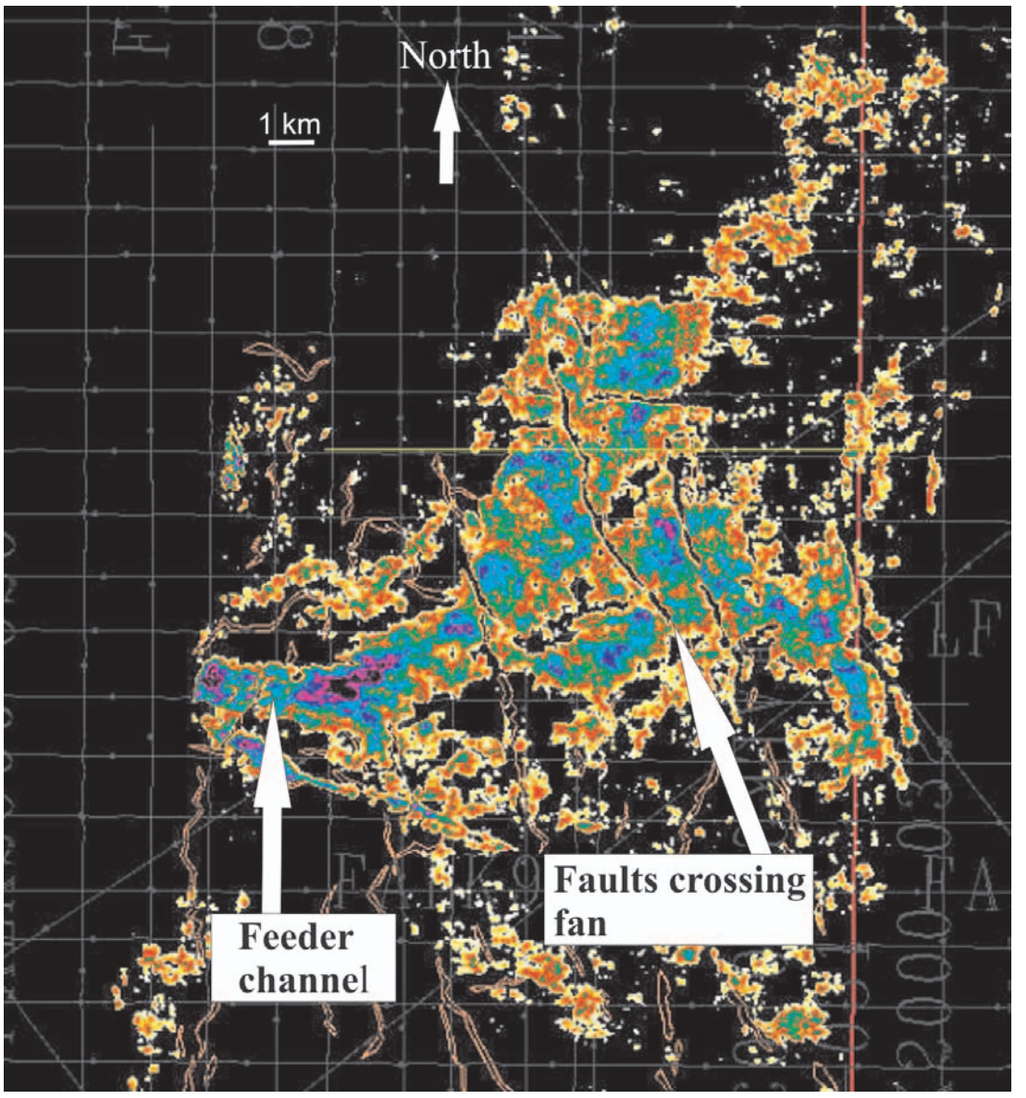

Fig. 8. "StratAmp" display of the Liz fan. The background amplitudes from the lacustrine claystones have been masked with a black marker band in this display in order to highlight the shape and intensity of the amplitudes over the Liz fan.

However, such deltas have been described slightly further north along the eastern basin margin (Richards and Hillier, 2000 a).

Although seven fans have been mapped on the new 3D seismic data in the central or eastern parts of the eastern depocentre (Fig. 7), only three of these are demonstrably derived from the eastern margin of the basin; the remainder are discussed below in the section on eastern depocentre fans of uncertain provenance.

The three fans that can be tied back to the eastern margin are here named the Helene, Ruth and Rachel fans (Fig. 7). The Helene fan lies within the late syn-rift succession and is probably of Tithonian age; it is therefore one of the oldest fans identified in the basin (Fig. 6). Although this fan cannot be tied back to any definitive channel, its morphology and orientation (Fig. 7) suggests that it was derived from a sediment transport system flowing NWwards down a relay ramp formed at an eastern margin offset.

The Ruth fan occurs at the base of the early post-rift section, and is probably of Valanginian age (Fig. 6). It is a fairly laterally restricted sand body, and like the Helene fan, appears to have been sourced from a nearby relay ramp at the basin margin. The Ruth fan feeder channel has been partially mapped on the new 3D dataset, and exhibits a convex upwards pattern of reflectors, possibly representing compactional drape over a sandstone plug, and lending confidence to the interpretation that the down-slope attached fan is probably sandy.

The Rachel fan also lies within the early post-rift interval, but is younger than the Ruth fan and is probably of Barremian age (Fig. 6). It interfingers with the topmost parts of the thick lacustrine source rock

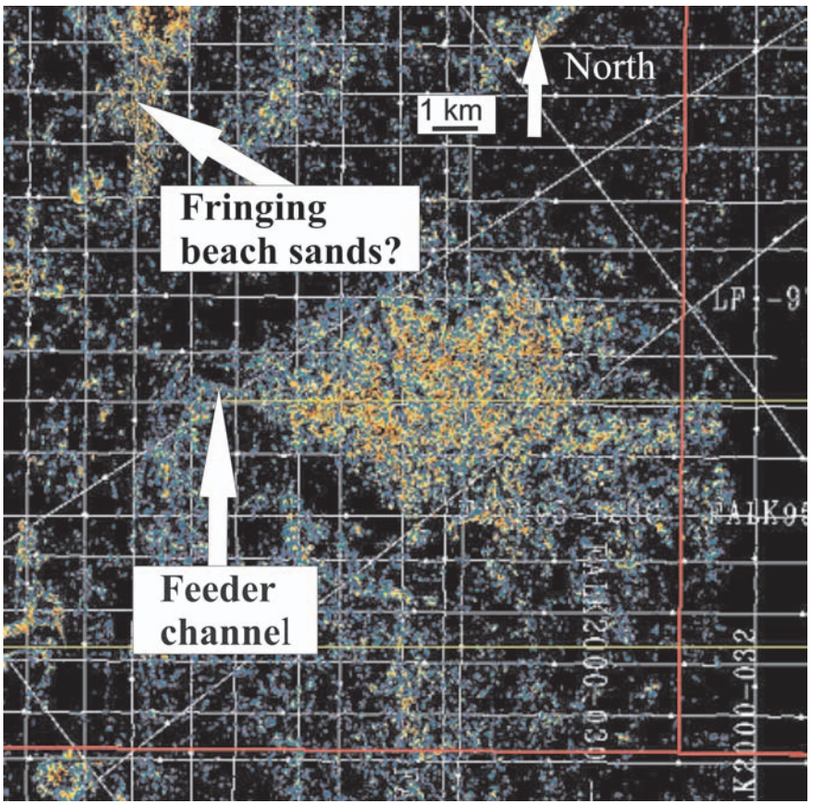

Fig. 9. "StratAmp" display of the Beth fan. The background amplitudes from the lacustrine claystones have been masked with a black marker band in this display in order to highlight the shape and intensity of the amplitudes over the Beth fan.

in the basin. Rachel has a distinctive, multi-fingered "StratAmp" anomaly (Fig. 10). It is also attached (Fig. 7) to a NE-SW oriented feeder zone channel formed in a significant incised valley up to 1 km or so wide. This feeder channel and its associated basin margin nick point is imaged on 2D seismic data just to the north of the new 3D dataset.

The Rachel fan covers an area of about 52 km^2. It appears to have been deflected southwards, into the deepest area adjacent to the basin bounding fault after entering the basin along the relatively long and narrow feeder channel (Fig. 7) at its northern end. Such deviations in the main sediment migration pathways, away from the sediment entry points at relays/transfers, and then into the areas of maximum displacement adjacent to faults, are commonly observed in rift basins (see examples in Leeder and Gawthorpe, 1987; Gawthorpe and Hurst, 1993; Eliet and Gawthorpe, 1995; and Trudgill, 2002).

EASTERN DEPOCENTRE FANS OF UNCERTAIN OR NORTHERLY PROVENANCE

Of the seven fans that can be mapped out along the eastern margin of the basin (Fig. 7), four could not unequivocally be linked genetically to the eastern margin in the same way as the Ruth, Rachel and Helene fans described above. These four fans of uncertain origin are here named Jenny, Emma, Phyllis and Joanne.

The Jenny and Emma fans occur at the same stratigraphic level as the Liz fan on the opposite margin, and are therefore interpreted as being of ?Valanginian age, and are located within the transitional zone between late syn-rift and early post-rift successions. The Phyllis fan lies within the late syn-rift section, stratigraphically between the Helene fan below and the Joanne fan above. The Jenny, Emma and Phyllis fans are only partially covered by the new 3D seismic survey (Fig. 7), with their northern extensions lying beyond the limits of the dataset. Therefore, it is not possible to identify where these fans were derived from; they may be attached to the eastern basin margin to the north of the 3D dataset, but it is equally conceivable that they represent deep-lacustrine fans derived as turbidites from deltas prograding into the lake from the north or NW.

The Joanne fan is also located within the transitional zone between late syn-rift and early post-rift successions, but at the base of it; this fan is also therefore probably of ?Berriasian age. It is not possible

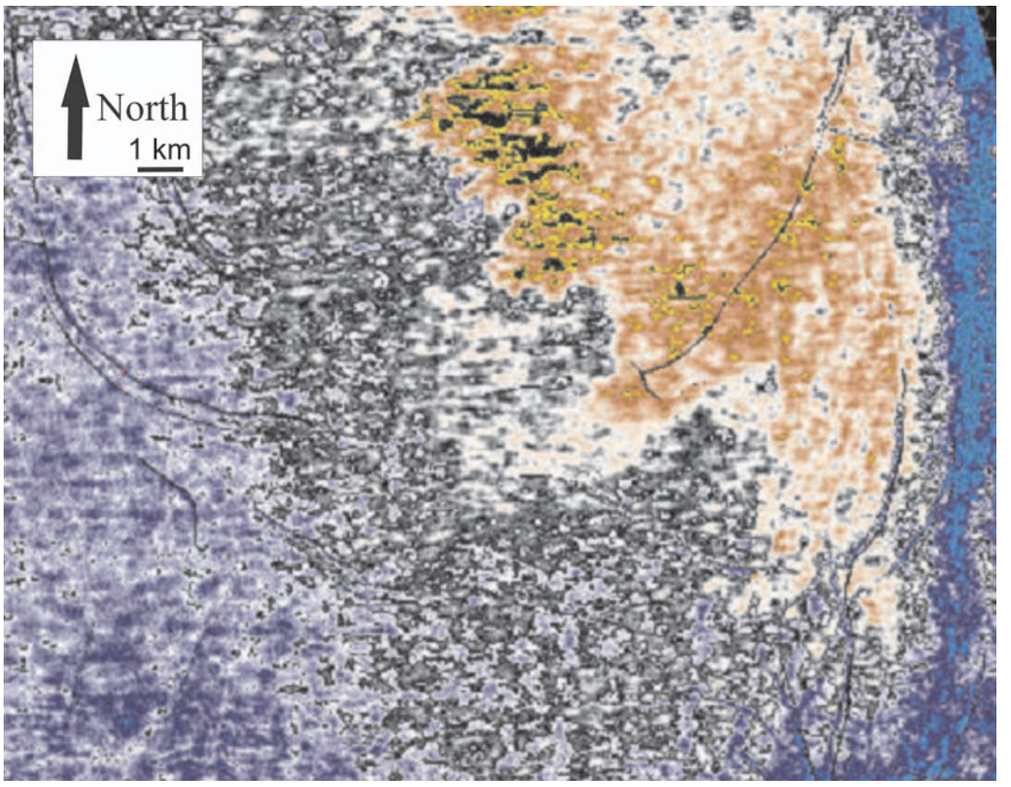

Fig. 10. "StratAmp" display of the Rachel fan. The background amplitudes from the lacustrine claystones are shown in blue to grey tones, whereas those from the fan are in bolder colours.

to map the source of the Joanne fan, although its NE-SW elongation (Fig. 7) suggests that it may possibly have originated from the same region as the stratigraphically younger Rachel fan (i.e. from the margin immediately to the NE).

FANS IN THE MALVINAS BASIN

No Cretaceous fan systems have been reported previously from the eastern part of the Malvinas Basin (Fig. 1). However, interpretation of reconnaissance exploration 2D seismic data acquired over the eastern margin of the Malvinas Basin by Spectrum Energy in 1995 has now facilitated the identification of large prograding fan systems that appear to have migrated off the Falklands Platform towards the SW, away from the Falkland Islands. These features have not been penetrated by any wells; the nearest well tie (*Salmon X-2* in the central part of the Malvinas Basin) is some 90 km or so west of the progrades, and therefore provides little insight into their internal nature.

The prograde/fan units identified on the eastern margin of the basin are bounded, above and below, by two prominent seismic reflectors (Fig. 11). The base of the succession is marked by a regionally correlatable reflector of probably base-Turonian age, defining the top of the Margas Verdes Formation/base of the Middle Inoceramus Formation in the *Salmon X-2* well to the west. This reflector is here termed the "Intra-Cretaceous Marker". At the top of the prograde/fan interval is a regionally correlatable reflector of probable Santonian age, which may define the top of the Middle Inoceramus Formation in the *Salmon X-2* well. Within the Malvinas Basin, the prograde/fan package is therefore located within the MS3 megasequence as defined by Galeazzi (1998), in a succession dated by him as between 91.5 and 85 Ma.

Although no well penetrations allow the lithology or environment of deposition of this prograde system to be interpreted, it is likely to be a clastic-dominated succession on the basis of its steeply-dipping progrades. As with the fans described above from the margins of the North Falkland Basin, these features appear to have been derived from a hinterland area comprising Palaeozoic sedimentary rocks possibly dominated by quartz-rich coarse clastics. Near the toes of the prograding fan units, the coherency of the seismic reflection signal is disrupted in a diffuse, vertical, funnel-shaped zone (Fig. 11) that might indicate vertical gas migration from toe-set sandstones.

Unlike the North Falkland Basin, no distinctive tectonic lineaments are evident to the SW of the Islands that might provide obvious sediment entry

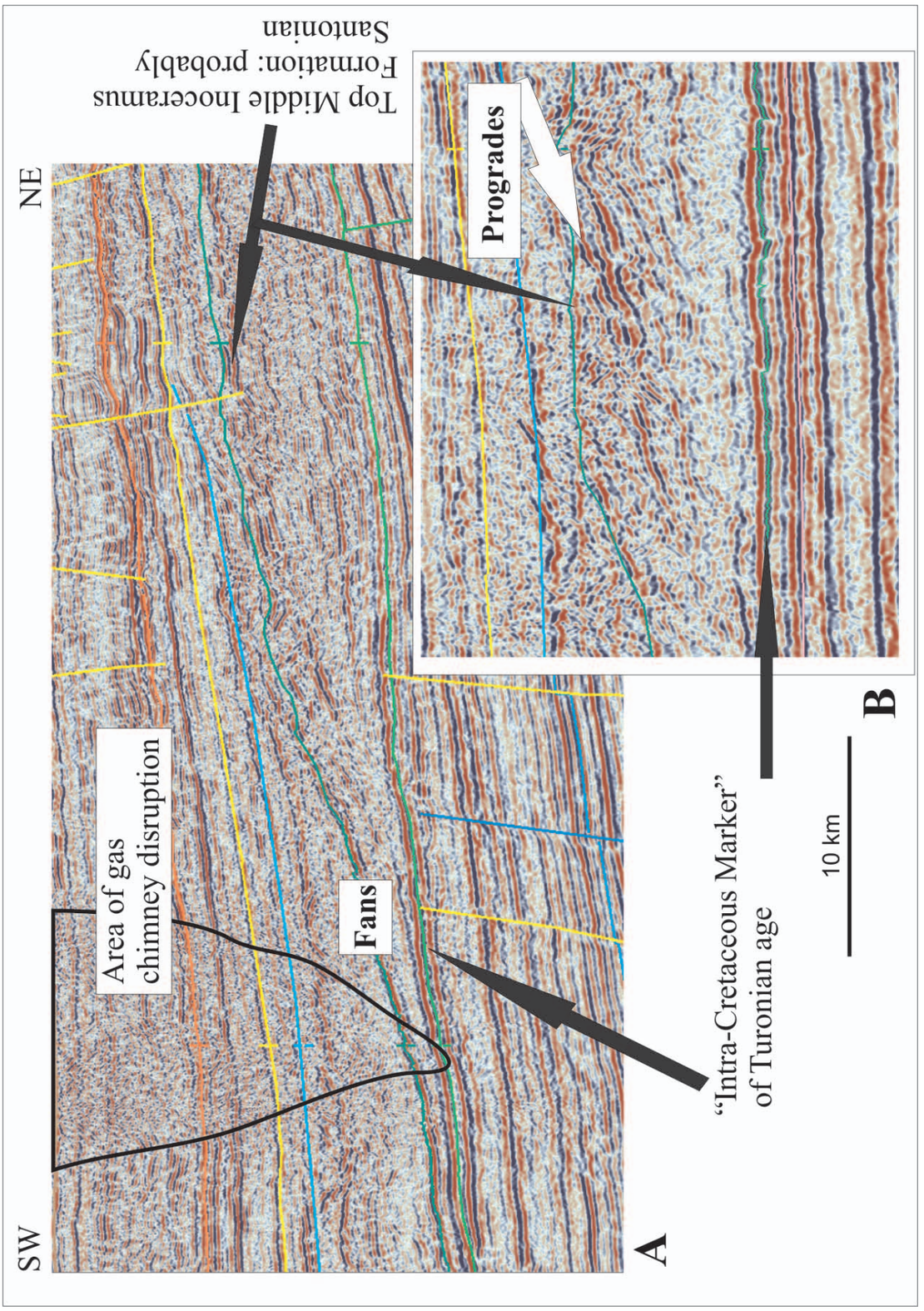

Fig. 11. Two parallel seismic sections oriented SW-NE across the eastern margin of the Malvinas Basin, illustrating the fans. (A) shows the gas chimney disruption at the toe of the fan. (B) shows apparent progrades within the fan body. Data supplied courtesy of Spectrum Energy and Information Technology Ltd., from a speculative survey across the eastern margin of the Malvinas Basin, acquired in 1995.

pathways for sand deposition into the eastern side of the Malvinas Basin at this time. Furthermore, the Malvinas Basin was undergoing thermal sagging from the Late Jurassic through the Cretaceous (Galeazzi, 1998), and was therefore not undergoing active rifting. It is therefore unlikely that the fans are related to significant fault activity along the basin margin.

The fans are mapped only to the SW of the Islands, and appear to prograde towards the structurally deeper part of the Malvinas Basin. The axis of the Malvinas Basin changes from a more-or-less NNW-SSE orientation, to take on an east-west orientation immediately south of the Islands, where it merges with the South Falkland Basin. Surprisingly, the fans do not appear to prograde into this deep basin immediately to the south of the Islands, although the lack of evidence here could be associated with the poorer quality of data available at present in this deeper water zone adjacent to the Scotia/South America plate boundary, where seismic data quality is reduced by the proximity of a wide fault zone.

FANS IN THE FALKLAND PLATEAU BASIN

Large-scale, wedge-like features of inferred mid-Cretaceous age have been described previously from the Falkland Plateau Basin (Platt and Philip, 1995; Richards *et al*.,1996 b) as prograding lowstand wedges, deltaic deposits or shelf margin fan systems. Both of these sets of authors also noted the presence of associated chaotically bedded, mound-like surfaces representing probable lowstand or basin-floor turbidite successions, although Richards *et al*. (1996 b) did not rule out the possibility that these features are slump masses. These wedge-like fans and associated deposits were mapped and interpreted on a regional reconnaissance seismic grid with a wide spacing (up to 50 km between dip lines) acquired in 1993.

Five distinct fan units are recognised in the Falkland Plateau Basin. The oldest fan is here called Fan System I: it is possibly of Jurassic age. This fan appears to pass eastwards into a zone of probable sills, which mask its downslope character. Fan Systems II, III, IV and V are named in progressive younging order (Fig. 12). These prograding successions are tentatively interpreted as Albian to Cenomanian age (Richards *et al*., 1996 b).

The four Cretaceous fans (Fan Systems II through V) step successively basinwards into the Falkland Plateau Basin (Fig. 12). This may indicate continued uplift of the hinterland area, with progressive basinwards stepping of deposition as the coastline retreated during hinterland upwarp.

The regional reconnaissance grid (of 1993 seismic) used to interpret these fans does not allow a definitive point source of entry into the basin to be accurately defined. However, the regional faults map (Fig 1) based on the work of Richards *et al*. (1996 b) suggests that there are several NW-SE oriented faults that cross-cut the NE-SW oriented basin margin at right angles, and these may form sediment entry points into the basin. Interestingly, these NW-SE oriented faults are possibly genetically linked to the transfer faults that offset N-S basin margin faults in the North Falkland Basin (Fig. 1), and which also provide the sediment entry points for the fans there also.

CONCLUSIONS

A number of fan bodies have been identified from seismic data and have been mapped in the North Falkland, Malvinas and Falkland Plateau Basins. The North Falkland Basin fans are of presumed Tithonian to Barremian age, whereas the Malvinas Basin fans are of Turonian to Santonian age, and correspond with a period of non-deposition over at least parts of the North Falkland Basin. The fans in the Falkland Plateau Basin are probably older than those in the Malvinas Basin. All of the fans form potential targets for the next phases of hydrocarbon exploration.

The North Falkland Basin fans provide a play concept and source of potential reservoir sands which is untested by drilling in the basin to date. Several of the fans are clearly imaged on “StratAmp” displays, and are interpreted to comprise distinct sandstone bodies in direct fluid connection with mature oil source rocks, immediately beneath a proven and effective regional seal. The fans are derived from a Palaeozoic hinterland, and are, at least on the western margin of the eastern depocentre of the basin, related to deltas that prograded off the platform area. On both sides of the eastern depocentre, the fan sediment appears to have been introduced into the basin along transfer zones and/or relay ramps offsetting the N-S extensional fabric of the basin margins.

A number of potential direct hydrocarbon indicators such as flat spots and near-surface pock-marks are associated with the fans and the feeder channel systems that are observed attached to some fans in the North Falkland Basin. These provide an additional incentive to target these fans during the next drilling phase in the basin.

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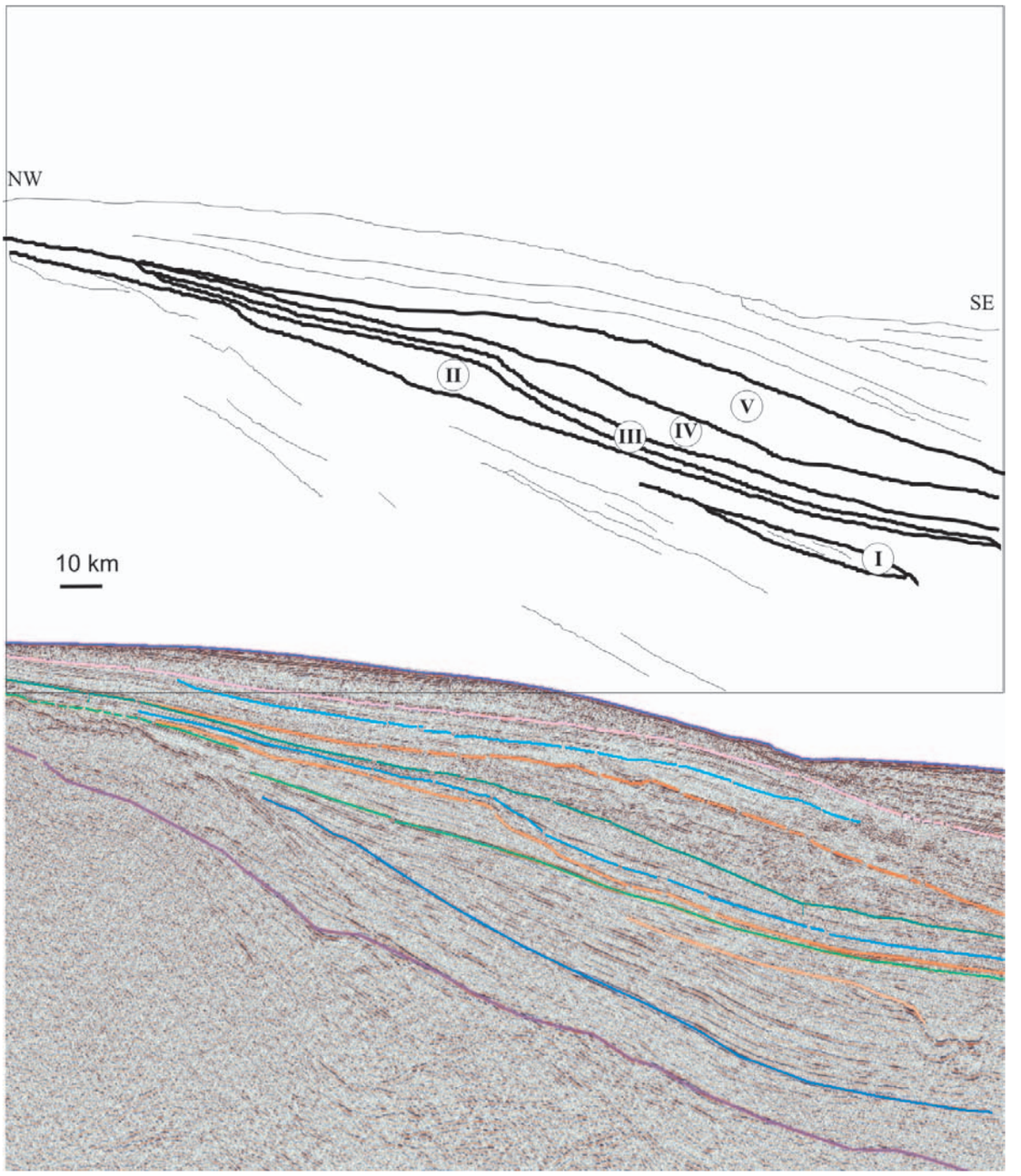

Fig. 12. Seismic section (and line drawing) oriented NW-SE across the western margin of the Falkland Plateau Basin, illustrating individual fans labelled I to V. Seismic acquired by Western-Geco, 1993.

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