Interactive interpretation of a submarine fan, offshore Ireland: A case history

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During the Eocene, a series of submarine fans developed in the Porcupine basin off the southwest coast of Ireland. Interactive interpretation of one—the Clontarf fan—shows the successive development of four sequences. Seismic facies analysis of these sequences suggests a progressive evolution from a more distal to proximal environment during deposition of the fan. Seismic facies mapping reveals an extensive series of sand-prone distributary systems in the youngest fan sequence. Amplitude anomalies suggest that this and other fans in the basin are favorable stratigraphic and/or structural traps for hydrocarbons.

The Porcupine basin is an oval-shaped reentrant in the shelf margin southwest of Ireland (Figure 1). The basin measures approximately 300 km long in a north-south direction and 120 km wide in an east-west direction. Subsidence began in the lowermost Cretaceous, and rifting extended from the Berriasian through Hauterivian (see *Structure and development of Porcupine Seabight sedimentary basin, offshore southwest Ireland,* Masson and Giles, 1986, AAPG *Bulletin*). Continued subsidence and sedimentation subsequently resulted in a thick section that exceeds 7 km in the deepest portion of the basin. Cretaceous sedimentary basin fill is composed of a heterogeneous succession of environments and lithofacies. During the Cretaceous, volcanic intrusions were emplaced in the lower part of the sedimentary fill. Chalk was the principal lithofacies deposited in the Upper Cretaceous. In the Lower Tertiary, subsidence accelerated, resulting in a succession of deep-water siliciclastic environments. Present water depths in the area of investigation exceed 1000 m.

Floored by continental crust, the basin has a medial volcanic ridge oriented north-northwest to south-southeast. The eastern basin margin is oriented in the same direction. Masson and Giles inferred that Hercynian movements of the Late Paleozoic produced zones of weakness having a north-northwest to south-southeast orientation. A subsidiary fault trend oriented north-south to northeast-southwest is associated with the Permian through Jurassic history of the basin. During this time the primary tectonic setting was that of a shelfal succession on a passive margin. Rifting broke this succession apart in the Lower Cretaceous. The Porcupine basin is also marked by a broad north-south gravity low that mirrors bathymetric trends. Gravity modeling suggests the deep Porcupine basin was formed by subsidence of an area of thinned continental crust.

Wells in the northern part of the basin have penetrated shallow water sediments, including some coals. During the Paleocene and Eocene, an extensive siliciclastic depositional system prograded into Porcupine basin from the north, forming a thick section that thins dramatically from north to south (Figure 2). This differential infill, combined with continued subsidence, formed a pronounced bathymetric gradient between the margins of the basin and its center. During the Eocene, a series of submarine fans developed seaward of the Eocene shelf margin. In east-west seismic profiles, these appear as a series of distinct mounds. In plan view, each of the submarine fans has an elongate oval shape. Internal reflection character suggests that each submarine fan was sourced from a different point around the periphery of the basin. In the following section we will describe the seismic stratigraphy and internal development of one of these fans.

The Clontarf fan, located in the west central portion of the basin, was selected for detailed investigation. A grid of seven east-west and four north-south lines was available for us to investigate the seismic stratigraphy of this fan. Seismic data were acquired by Merlin Geophysical in 1981, using an energy source of 950 in^3 air guns and a cable length of 2920 m. The data were sampled at 4 ms. Processing included finite difference migration and a time-variable filter. The data were scaled using a short AGC operator. Data loaded into a Landmark workstation consisted of a subset of the final processed data—through migration. Spacing of the lines in both the north-south and east-west directions is 6.5 km.

The Clontarf fan is ovoid in shape with the long axis oriented northwest-southeast, tapering to the southeast. It is approximately 40 km long and 25 km wide at maximum extent. The extreme northwestern tip of the fan is unknown because it extends beyond the survey limits. The total thickness of the fan is about 600 m. In plan view, it is similar in shape to the Rhone fan and the Indus fan, but the Clontarf fan is much smaller and thinner. The top of the Eocene siliciclastics underlying the Clontarf fan are recognizable by toplap. Siliciclastics which infilled around the Clontarf fan show onlap and downlap in areas between the fan and those adjacent to it. Interpreted as fine-grained, deep-water sediments, these sediments provide a seal to the Clontarf fan.

The fan is divisible into four internal sequences. Evidence for this consists of the external geometry of each sequence, as well as internal downlap and onlap at the margins of the fan. We have labeled these as sequences A through D. Sequence boundaries are shown in Figure 3. The top of the Eocene prodelta is marked by the lowermost boundary, shown in red. Sequence A, the oldest in the Clontarf fan, is shown by the purple horizon. Geometrically, it is a sheet and extends across the entire basin. Internally, the purple sequence is characterized by parallel reflectors with little variation. The second sequence (B), shown by the green horizon, also has a sheet geometry but lacks the regional extent of the purple sequence. Internally, most of the reflectors are parallel, although some prograding clinoforms are found. The third sequence (C), marked by the orange horizon, is the oldest sequence that shows a distinctly mounded appearance in cross-section. Internally, seismic facies in the orange sequence are a combination of hummocky clinoforms and parallel reflectors, with shingled reflectors occurring toward the periphery of the fan. The youngest (D) is shown by the blue horizon. Externally, it has a very strong mounded expression. Internally, the seismic facies are a combination of hummocky clinoforms and parallel reflectors in the northwestern or proximal portion of the fan. The percentage of hummocky clinoforms within the sequence consistently increases downdip to the southeast. Shingled reflectors are found at the margins of the fan in the blue sequence.

Sequence boundaries were independently identified on two north-south and two east-west lines. Then these were correlated and extended throughout the entire grid of lines on which the fan appeared. Figure 4 is a fence diagram showing the position of the sequence boundaries on each of the lines analyzed. The vertical lines mark intersections of crossing lines of control. On the workstation, fence diagrams like these can be rotated and viewed from many different perspectives, allowing the analyst to appreciate the 3-D configuration of each sequence in the Clontarf fan. Computer-generated horizon maps of sequence boundaries can also be viewed in perspective, and it is possible to compare the attitude and geometry of several contoured surfaces in this way.

As seen in seismic sections, the geometry of the sequences has been somewhat distorted by additional subsidence that occurred after deposition. In order to approximate the original external geometries and to examine the progressive development of the Clontarf fan, horizon flattening can be used. The relative thickness of the four sequences becomes obvious when sequence A at the base is flattened on the top of the Eocene prodelta, sequence B is flattened on top of sequence A, and so on. When these flattened sequences are displayed in the same order that they were deposited (Figure 5), progressive change from the sheet geometry of sequence A to the mounded geometry of sequence D is evident.

Maps and cross-sections. One of the most utilitarian aspects of the workstation is the ability to create a series of maps that shows sequential development. First, an isochron contour map of the total fan thickness was generated to show the location and extent of the fan. Seismic control does not confirm closure in the northwestern part of the fan. Contours derived from this map were overlaid on maps of each sequence.

Figure 6, for example, shows three different aspects of sequence D. The left side displays the original 2-D isochron control as ribbons. The map in the center is a smoothed, gridded version of this control, with relative thicknesses highlighted by the color bar on the right. Creation of this gridded map from 2-D control took place in three stages. First, a triangulated surface was fitted across the 2-D control, which in this case represented an isochron map between the top of sequence C and sequence D. Second, a grid was defined, and the system wrote the interpolated isochron values into each grid point. Third, the linear interpolated map was smoothed. Overlying the sequence map is the contour map, in two-way traveltime, showing total thickness of the fan.

The isochron map of sequence A, the oldest portion of the fan, exhibits a maximum of only 15 ms variation in thickness. In contrast, the isochron map of sequence D shows that over 500 ms of section were deposited along the axis of the fan. As the fan developed seaward of the Eocene deltaic margin, maximum differentiation between the fan and the surrounding deeper portion of the basin occurred during deposition of sequence D. Thinning into troughs bordering the fan is clearly evident in Figure 6.

Interactive display allowed us to create a set of panels consisting of a series of cross-sections across the length and width of the fan. This kind of display facilitates the examination of downdip changes in geometry and seismic facies from the more proximal to distal portions of the fan.

Another effective method for understanding the deposition of the fan is to display different aspects of data for the same line. Figure 7 is a zoomed view of sequence D in an east-west cross-section through the western half of the fan. The top panel is a seismic section display, while instantaneous phase is displayed in the center and reflection strength on the bottom. Windows like these may be displayed simultaneously on the same screen using 8 bit pseudocolor. The phase display in the center shows much more lateral continuity than regular seismic amplitudes. The strength of the reflection interfaces at sequence boundaries C and D is seen best in the display at the bottom.

At shotpoint 205 in Figure 7, a slight bump at the top of sequence D is distinctly visible. After examining various attribute displays, we interpreted this feature as the result of differential compaction between a sand-prone channel system and shale-prone interchannel deposits. A similar feature can also be seen at the top of sequence C near shotpoint 450.

Seismic facies within the Clontarf fan exhibit gradational changes both vertically and horizontally. Sequence A, as noted earlier, is characterized internally by parallel reflectors. But the relative percentage of hummocky clinoforms within the fan increases upward, reaching a maximum in sequence D. Laterally, the relative percentage of hummocky clinoforms increases downdip from north-west to south-east in sequence D. Hummocky clinoforms are interpreted as the distributional axes of more sand-prone facies within the fan. The degree of bifurcation is interpreted to increase downdip, as seen in channel systems of many modern submarine fans. The distribution of hummocky clinoforms in the lower and upper half of sequence D was mapped separately and contoured to show the distribution of channel-prone facies. Figure 8 shows a schematic representation of the channel system in the lower half of sequence D overlaid on the contoured outline of the fan. We believe the channel systems reached a point of instability and shifted position during the development of sequence D, resulting in different channel configurations during deposition of the lower and upper halves of the sequence.

The purpose of seismic facies mapping is to provide insight into the sedimentological history of the sequence being mapped. Thus, if we proposed a well location to test the hydrocarbon potential of the Clontarf fan, we would combine stratigraphy and structure to choose an optimum location. When the two-way traveltime section is converted to depth, the slope on the top of the Eocene delta is flattened, becoming more nearly horizontal. This increases the presumed closure in the northern portion of the fan. A comparative overlay of the seismic facies and structure contour map suggests a local culmination in the northeastern portion of the Clontarf fan. We believe this constitutes a favorable prospect for testing the hydrocarbon potential of this submarine fan.

Before actually drilling the initial test, similar seismic strati-

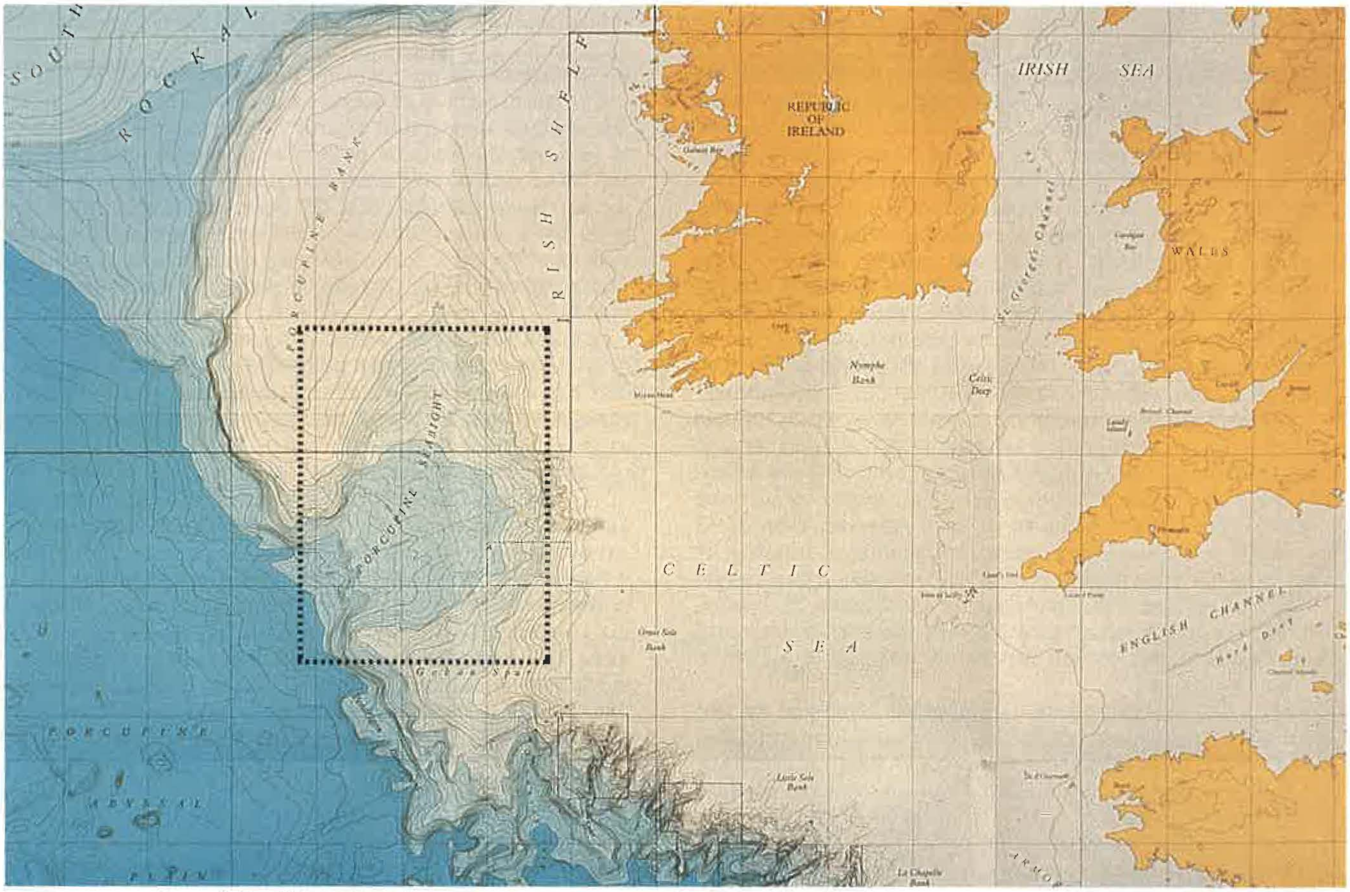

Figure 1. Location of the Porcupine basin.

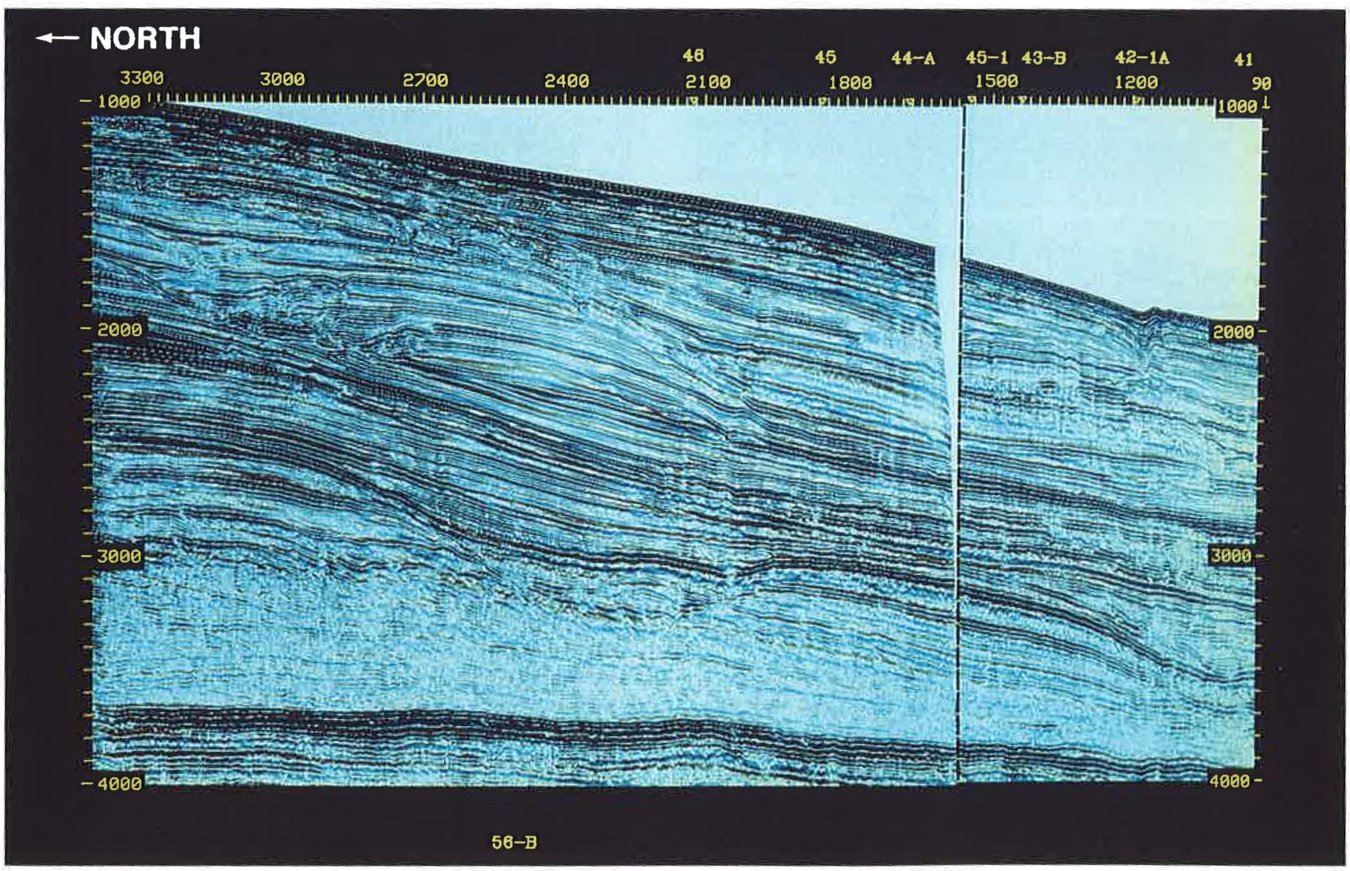

Figure 2. Variable density seismic profile showing Paleocene-Eocene delta (between 3.0 and 3.7 s) prograding from north to south.

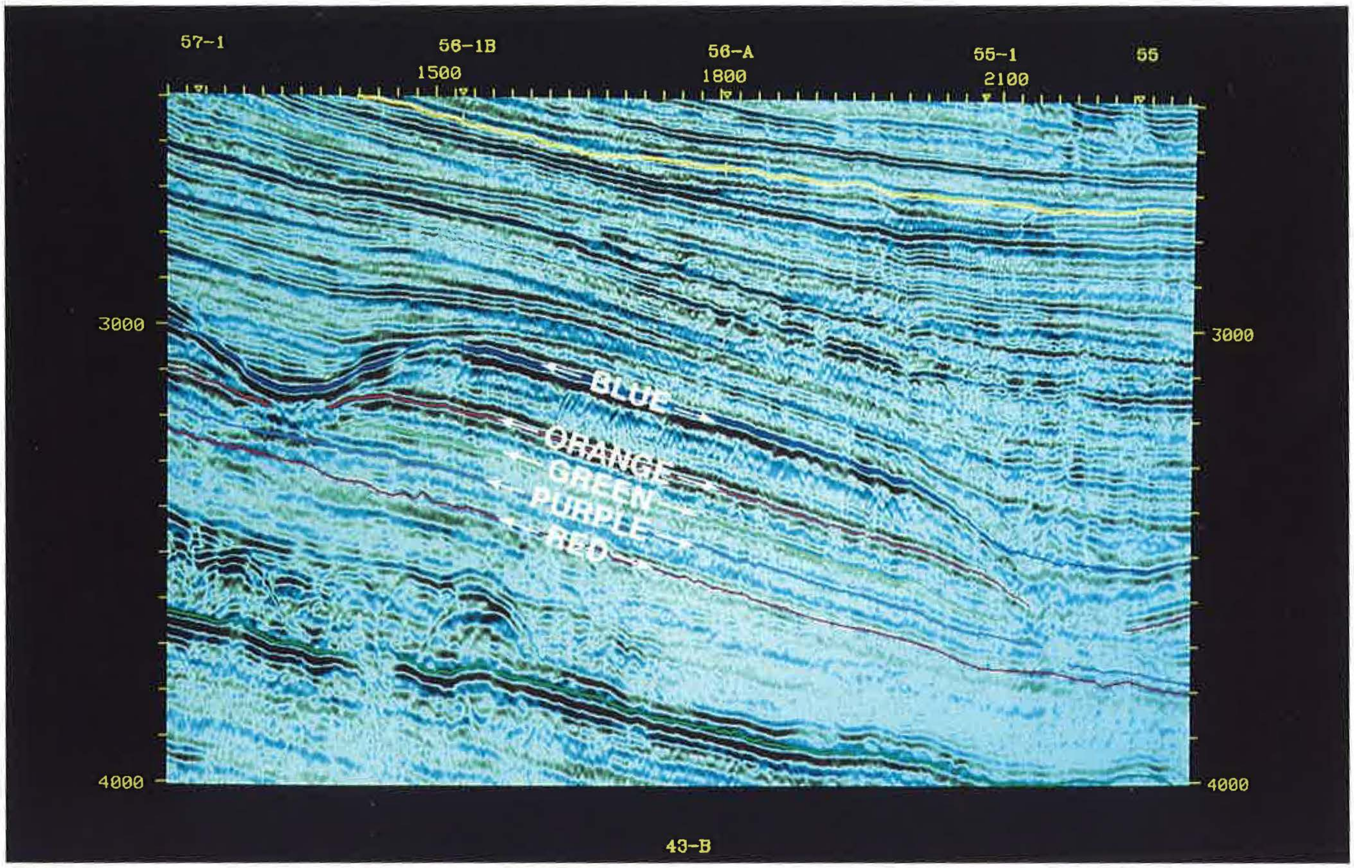

Figure 3. East-west cross-section of Clontarf fan. Top of Eocene, red; sequence A, purple; sequence B, green; sequence C, orange; sequence D, blue.

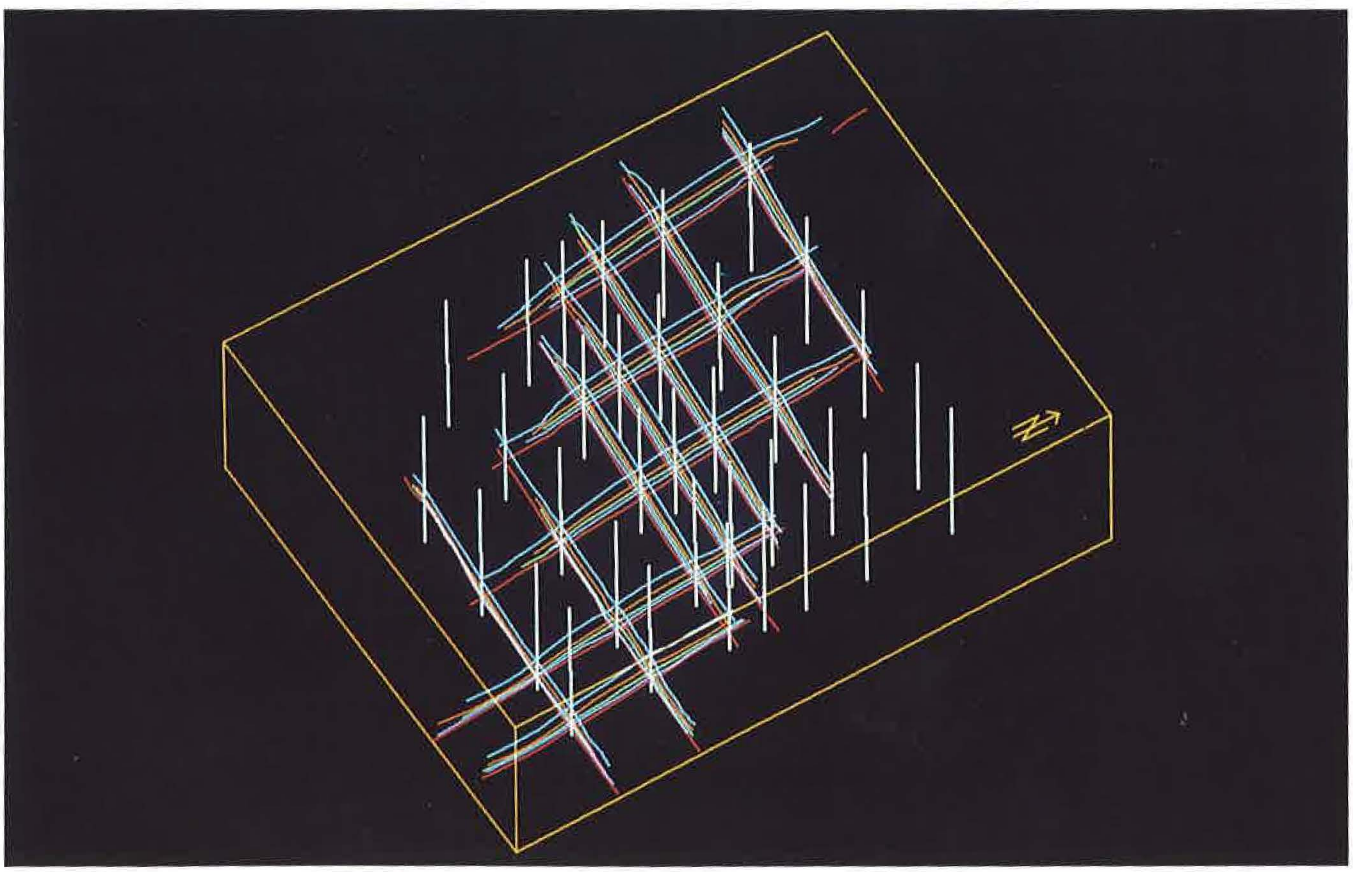

Figure 4. Fence diagram of the sequence boundaries in the Clontarf fan. The vertical lines show the intersections of crossing control lines.

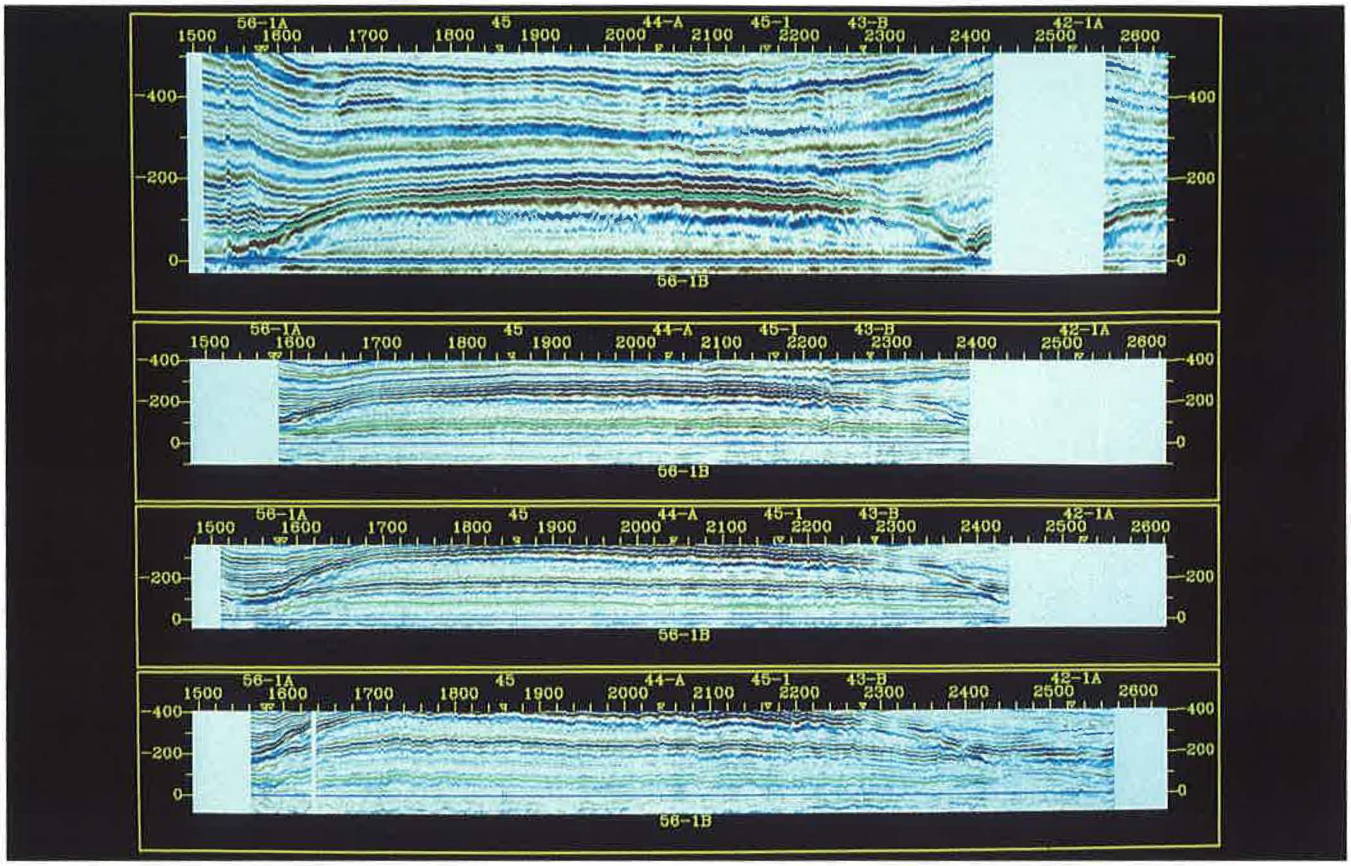

Figure 5. Four windows using horizon flattening to show relative thickness of sequences. D at top is flattened on C; A at base is flattened on Eocene prodelta. In each window, the top of that sequence is green; top of previous sequence is purple.

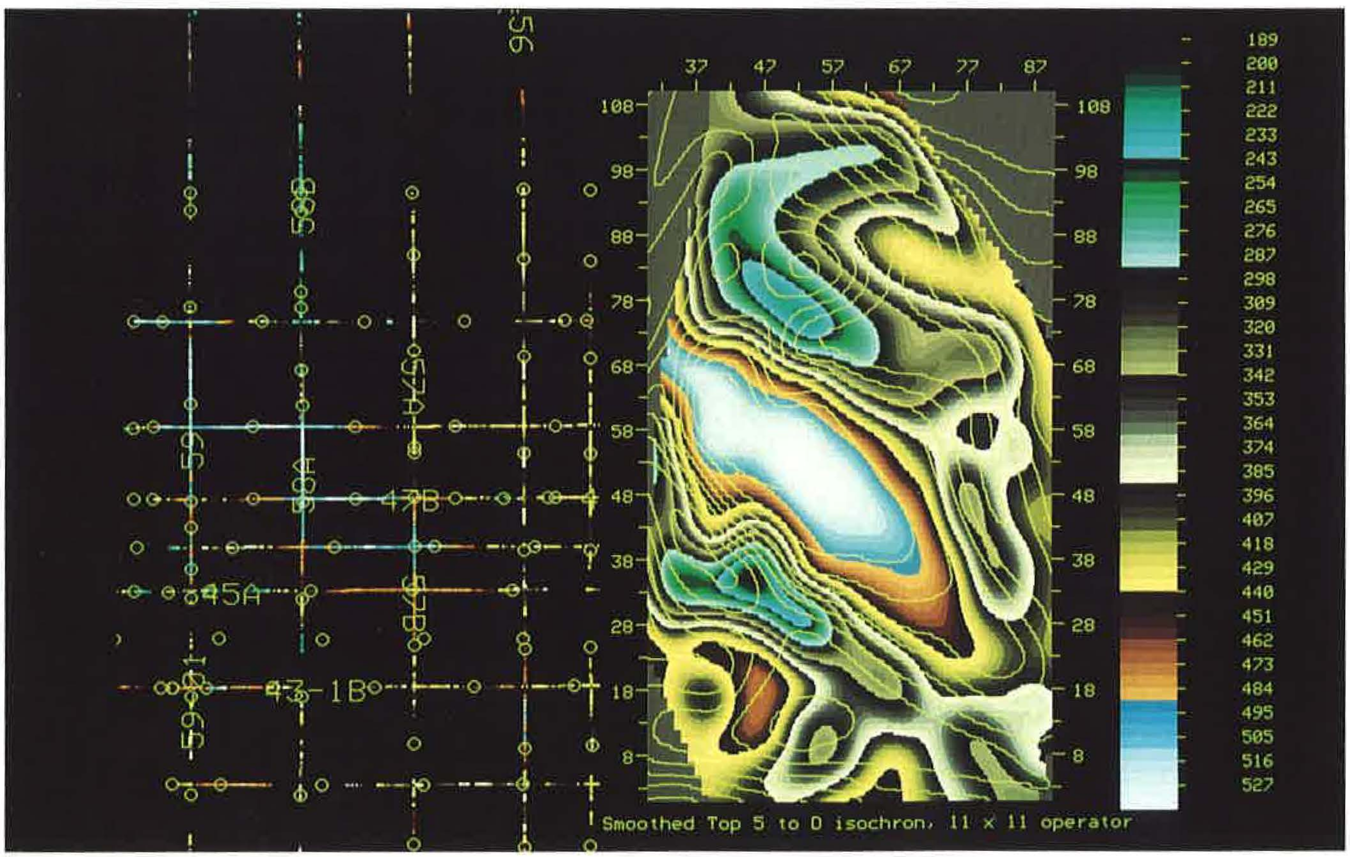

Figure 6. Isochron thickness map of sequence D with contours of the total fan thickness superimposed. Thickest section shown by grays/white along axis; thinnest sections shown by blue-greens in troughs bordering axis.

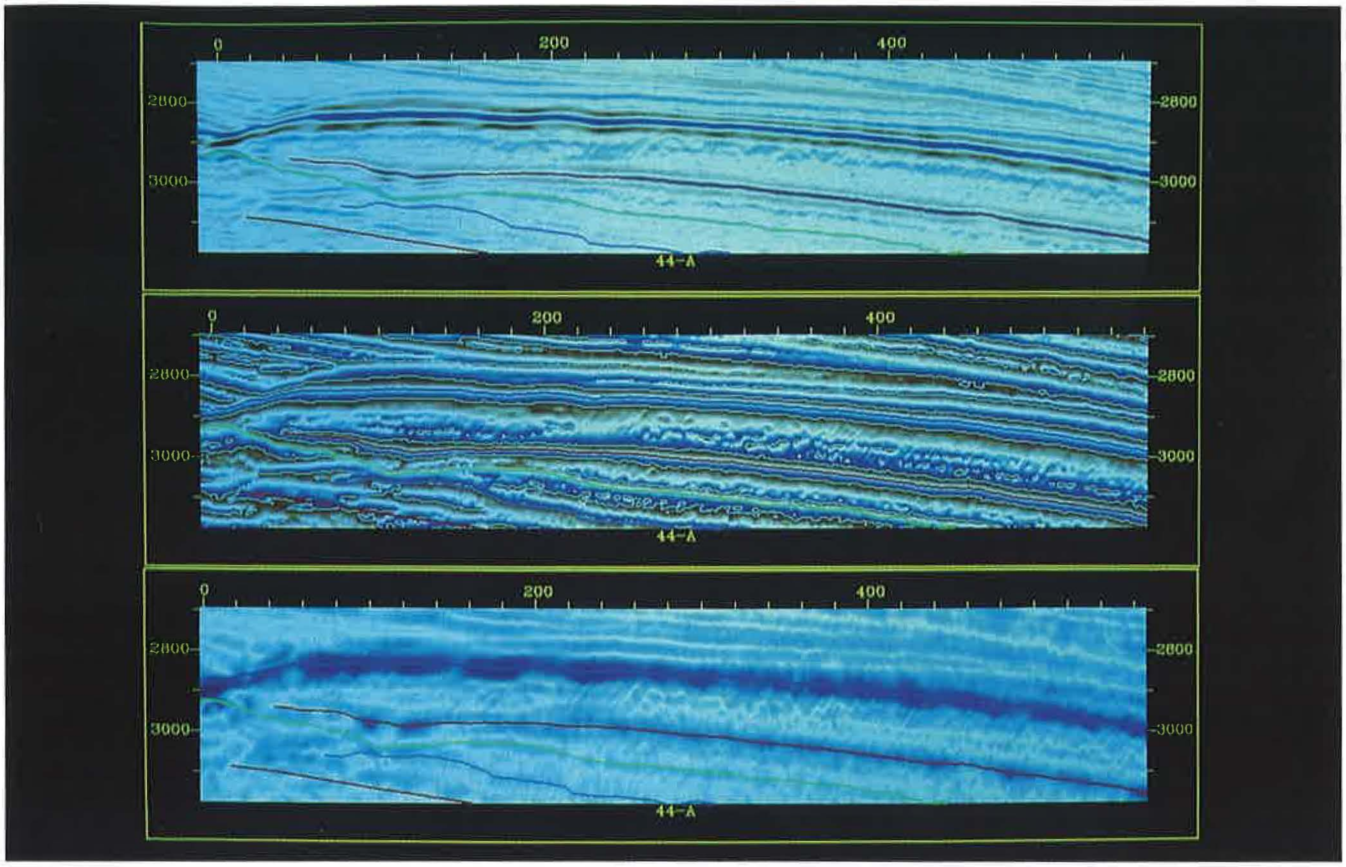

Figure 7. Different attribute displays of a single east-west line, with color-coded sequence boundaries. Top window shows a colored seismic section display; center, instantaneous phase; bottom, reflection strength.

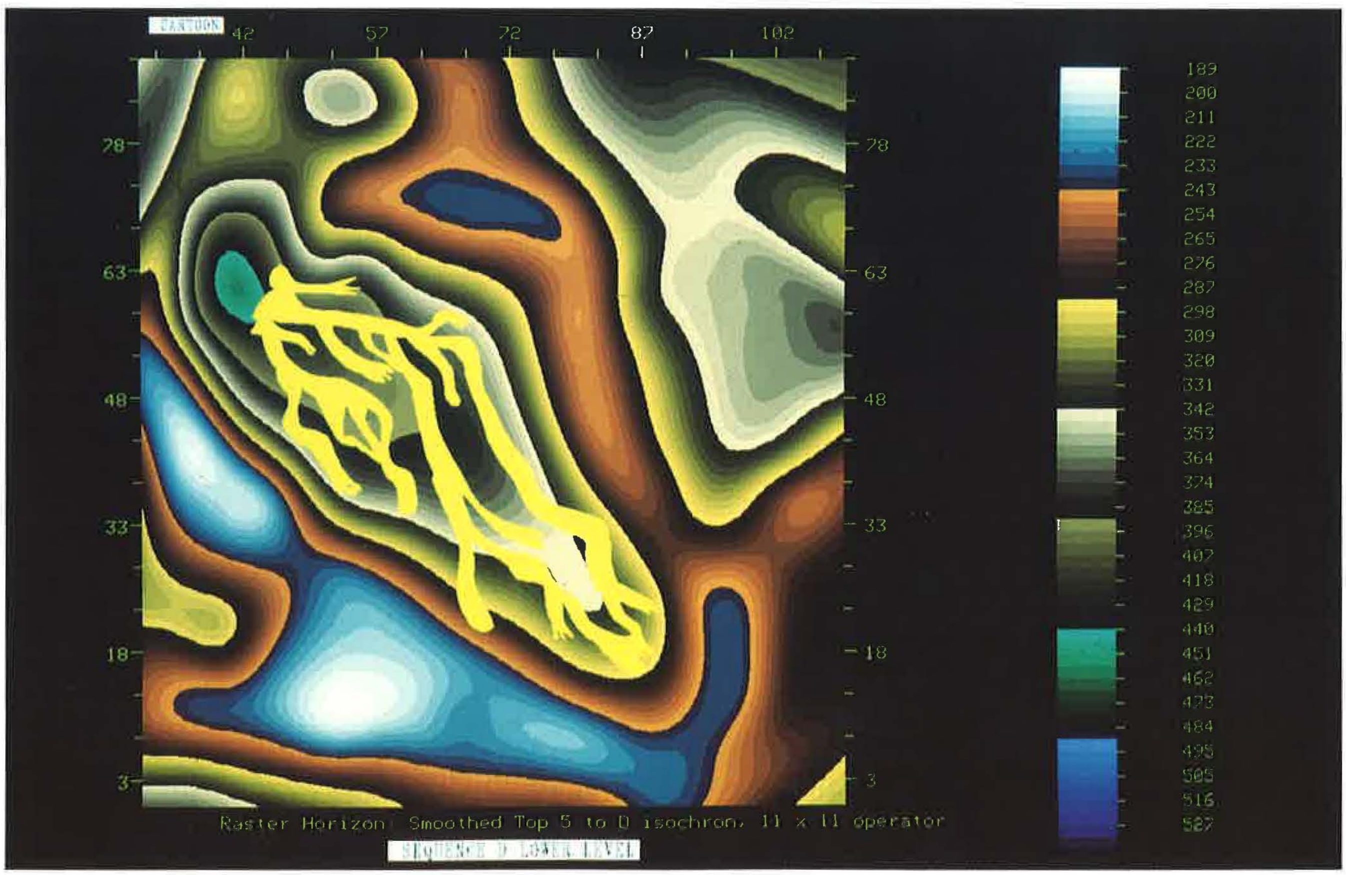

Figure 8. Distribution of channel-prone facies in lower part of sequence D, superimposed upon isochron thickness map of Clontarf fan.

graphic and facies analyses should be conducted for other submarine fans at this stratigraphic level, so the most promising fan could be selected. Two amplitude anomalies encourage us to believe hydrocarbons are reservoired in the submarine fans of Porcupine basin. The first anomaly is a flatspot at a local culmination on a fan located 40 km east of the Clontarf fan. The second is a gas chimney that occurs above the southeastern portion of the fan. Comparative facies analysis of overlying sequences suggest that the most probable source is sequence D in the submarine fan.

In conclusion, initial Lower Tertiary deposition in the Porcupine basin was dominated by the development of a deltaic succession sourced from the northern portion of the basin. Increased subsidence during this interval of time resulted in increased bathymetric differentiation between the margins and center of the basin. During the latter part of the Eocene, a series of submarine fans developed seaward of the Eocene shelf margin, sourced from different points around the periphery of the basin. The Clontarf fan developed in the western portion of the basin. Internally, the fan is comprised of four sequences, each of which developed in a more proximal setting than its precursor. From seismic sequence and facies analysis, environments are interpreted as a series of distributary systems that bifurcated in a south-easterly direction. Local highs within the fan sequence probably resulted from differential compaction between sand-prone and shale-prone lithofacies. Extensive development of sand-prone facies suggests that, under favorable economic conditions, the Clontarf fan will become a viable prospect.

Present water depths over the fan make it a rank wildcat. But recent discoveries in the southern hemisphere of submarine fans containing three billion barrels of reserves each should encourage exploration for sands in other basins also deposited in deepwater environments. LE

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