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Crustal Deformation Across the Galicia Bank of Offshore Iberia from Seismic Reflection Data: Processing, Interpretation, and Reconstruction

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

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ABSTRACT

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The Iberia Margin is an excellent example of a passive rift. Multi-Channel Seismic (MCS) data consisting of the Line 14 reflection profile from the 1997 Iberia Seismic Experiment were processed and interpreted. Enhanced processing attenuated pervasive water-bottom multiple noise. MCS data image an extensional terrain that includes the Ocean-Continental Transition (OCT). The Moho is imaged locally. Extended crust was restored to an unextended state to quantify deformation. Horizontal strain tends to increase seaward along dip; the average strain is 46%. Crustal-thickness data indicate an average crustal thickness of 9.9 km. With certain assumptions regarding the observability of extension, the presence of ‘pure shear’ exclusively, and initial crustal thickness, there is a major discrepancy between the observed average crustal thickness and the average crustal thickness predicted by observed strain. The only satisfactory explanation is that crust has been removed by asymmetrical extension (simple shear).
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Chapter 1

Introduction to the Atlantic Margin of Iberia

1.1 Geologic History

The Atlantic margin of Iberia formed as a result of Mesozoic rifting. Evidence of lithospheric extension within this region is first observed during the Late Triassic (Hiscott et al., 1990; Louden et al., 1999). This was followed by three major phases of rifting up to the Early Cretaceous, with each phase separated by a period of subsidence (Moullade et al., 1988; Murillas et al., 1990; Pinheiro et al., 1996; Whitmarsh et al., 1996). The formation of oceanic crust commenced soon after, and the first seafloor-spreading anomaly observed in this region is the J anomaly, which lies between the M0 and M2 magnetic chrons (Tucholke et al., 1982; Chian et al., 1999). These, and other, magnetic features suggest that seafloor spreading started between 125 Ma and 130 Ma in the region west of the Iberia Abyssal Plain; and at approximately 115 Ma in the region west of the Galicia Bank (figure 1.1) (Verhoef et al., 1986). Thus it is generally accepted that rifting propagated in a south-to-north direction during Cretaceous time (Beslier et al., 1993; Whitmarsh et al., 1995; Whitmarsh et al., 1996; Louden et al., 1999). The above ages for the onset of seafloor spreading are consistent with drilling results (ODP Leg 149 Shipboard Scientific Party, 1993; Boillot et al., 1987; Sibuet et al., 1979; Mauffret et al., 1988).

Researchers generally agree that the final rifting phase lasted roughly 25 Ma off the Galicia Bank and roughly 15 Ma in the southern Iberia Abyssal Plain (Louden et al., 1999). However, some authors point to the apparent lack of syn-rift sequences on
reflection profiles (Wilson et al., 1996) and radiometric dating performed at ODP Site 900 (Feraud et al., 1996) as evidence that rifting may have lasted for a much shorter period in the southern Iberia Abyssal Plain.

The range of reasonable spreading rates at this latitude in the North Atlantic between the J anomaly (assumed to be roughly 124 Ma) and anomaly 34 (83 Ma) has been well constrained by the work of several authors. In 1978 Rabinowitz et al. reported a spreading rate of 8 mm/yr, while Whitmarsh et al. (1995) derived a spreading rate of between 9 mm/yr and 10 mm/yr for the same period.

It should be noted that the Iberia margin has experienced two minor episodes of post-rift tectonism. The first included a component of north-south compression associated with the Pyrenean Orogeny of the Late Cretaceous through Eocene. The second included a component of northwest-southeast compression associated with a compressional phase in the Betic Range of southern Spain during the Miocene (Murillas et al., 1990; Whitmarsh et al., 1996).

The margin is divided into three segments in the longitudinal direction, they are from south to north: 1) the Tagus Abyssal Plain, 2) the Iberia Abyssal Plain, and (3) the Galicia Bank (figure 1.1).

1.2 Significant Geologic Features

1.2.1 General

Although crustal thicknesses vary significantly with distance seaward, as well as distance north or south along the margin, the pervasive structural pattern of the entire survey area consists of rotated, mostly down-thrown to the west, normal fault-bounded
Bathymetry of the Iberia Margin

Figure 1.1: Regional map showing entire Iberia Margin. Bathymetry contours every 500 m. MCS lines are labeled and color coded to deployment sequence. OBS/OBH locations and ODP drill sites are shown. Significant geologic and geographic features are included. Modified from Unger, 1999.
crustal blocks striking between 345° and 360° (Beslier et al., 1993; Whitmarsh et al., 1995). As noted above, the presence of the J magnetic anomaly off Iberia indicates that seafloor spreading began at a point eastward of it. Plate reconstructions beginning with present configurations and going back to Chron M0 join the Galicia Bank of the Iberia margin to the Flemish Cap of Newfoundland (figure 1.2) (Srivastava et al., 1992). However, southward of this match the reconstruction leaves open a deep-water, 180 km wide region between the J anomaly and the base of the Iberia continental rise (Chian et al., 1999). This region is an unusually wide ocean-continent transition (OCT), and on the Iberia side has been found to consist of extremely thin continental crust (2-5 km) underlain by mantle peridotite serpentinized to varying degrees (Louden et al., 1999; Whitmarsh et al., 1996). The OCT is again expressed with similar geology in a region directly west of the Galicia Bank, but this region is much narrower than the broad southern region described above (Discovery 215 Working Group, 1998). The regional presence of serpentinized mantle peridotite is supported by the velocity structure of the area as constrained by seismic refraction studies (Whitmarsh et al., 1990). These refraction data indicate the presence of a 1.5 km thick layer of 7.42-7.55 km/s material, which is consistent with known velocities for serpentinized peridotite. The OCT has been the subject of great interest and numerous seismic and other geophysical studies in recent years (Beslier et al., 1993; Boillot et al., 1989; Hoffman et al., 1992; Pinheiro et al., 1992; Sibuet, 1992; Whitmarsh et al., 1990; Whitmarsh et al., 1993). This is because the OCT is believed to contain evidence regarding the final break-up of the continents and the initiation of seafloor spreading. Magnetic anomalies imaged in this region are consistent with the presence of long, roughly North-South trending, weakly magnetized crustal
Figure 1.2: Plate reconstruction of the North Central Atlantic at chron M0. Bathymetry contours at every 1 km. Lightly shaded regions represent sedimentary basins, while heavily shaded regions represent the resulting overlap between plate boundaries. Direction of plate motion is illustrated by dashed lines. JB = Jeanne d’Arc Basin, WB = Whale Basin, HB = Horseshoe Basin, OB = Orphan Basin, FC = Flemish Cap, CSB = Celtic Sea Basin, WAB = Western Approaches Basin, PB = Porcupine Basin, GLB = Galicia Bank, IGB = Galicia Interior Basin, LB = Lusitanian Basin, CB = Cantabrian Basin, NNB = North Newfoundland Basin, SNB = South Newfoundland Basin, IAP = Iberia Abyssal Plain, TAP = Tagus Abyssal Plain. Taken from Srivastava et al., 1992.
blocks. These magnetic features furthermore suggest that the crustal blocks are 7 to 30 km long, roughly the same thickness as oceanic crust, and were formed under the same stress regime that led to eventual seafloor spreading (Whitmarsh et al., 1995).

Previous researchers have noted the unusually large width of the extensional margin between both the Newfoundland margin and Iberia margin implied by the location of the presumed continent-ocean boundary at the J anomaly. Using finite element modeling, it has not so far been possible to explain the width of extensional terrains present between the conjugate margins with the simple thinning and stretching of preexisting continental crust (Bassi et al., 1993). To explain the observed extensional width, it becomes necessary either to add material to the margin or completely unroof the underlying mantle. In numerous locations throughout the OCT, continental crust appears to be partitioned by non-continental material. Some investigators believe these presumably non-continental features consist of volcanic/plutonic material that intruded the thinned continental crust after passive mantle upwelling produced adiabatic partial melting (White, 1992; Whitmarsh et al., 1993; and analogous to Hall, 1989; White et al., 1989). Other investigators suggest these features consist of tectonically denuded upper mantle material which is overlain by ‘islands’ of continental crust (Boillot et al., 1987). These features could also be some combination thereof.

1.2.2 The Peridotite Ridge

Throughout the West Iberia margin, the ocean-continent transition (OCT) is marked by a basement ridge trending north-south between latitudes 40°N and 43°N (figure 1.1). The ridge consists of serpentinized peridotite that has been sampled at
several ODP locations (i.e. site 897) (Sawyer et al., 1994), and is segmented into at least four parts. The strength of serpentinite is much lower than that of typical continental or oceanic crustal rocks, and its ubiquity within the OCT may have greatly influenced the development of the margin (Louden et al., 1999). It has been hypothesized using magnetic data and seismic reflection data that the ridge is bounded by oceanic crust to the west and highly extended continental crust to the east; and because of its location the ridge is inferred to be both the paleo-rift axis as well as the scar resulting from continental break-up. Furthermore, this ridge tends to parallel both the seafloor spreading anomalies to the west and other magnetic features to the east (Whitmarsh et al., 1995).

Following this interpretation, the ridge is believed to have been emplaced approximately 125 to 130 Ma ago when ultramafic basement was unroofed before the advent of seafloor spreading. The segmentation suggests that the northward propagation of rifting during the Cretaceous may have been discontinuous (Beslier et al., 1993; Whitmarsh et al., 1996). Results of ocean drilling (Whitmarsh et al., 1996) suggest that peridotite is exposed landward of the Peridotite Ridge in the Iberia Abyssal Plain. The peridotite ‘ridge’ may actually be a peridotite ‘region’ between unequivocal thinned continental crust and oceanic crust.

1.2.3 The Galicia Bank

The Galicia Bank is a structural feature recognized by bathymetry that is intermediate between that of the Iberia continental shelf and the Iberia Abyssal Plain (figure 1.1, figure 1.2). Continental basement shallows in this area and the crust is relatively thick (Sawyer and Zelt, 1999). Previous seismic reflection profiles across the
Galicia Bank indicate the same structural motif that is present throughout the margin: roughly north-south trending, landward-tilted fault blocks. These fault blocks become progressively down-thrown to the west on the seaward side of the Galicia Bank (Whitmarsh et al., 1996). As noted earlier, the Galicia Bank is the conjugate feature of the Flemish Cap on the Newfoundland margin (Chian et al., 1999).

1.2.4 The Galicia Interior Basin

The Galicia Interior Basin (figure 1.1) is a feature characterized by a deeper continental basement (compared with the Galicia Bank and the Iberia continental shelf) and a thicker sedimentary package. The structural framework is the same as that of the Galicia Bank, with the exception of a deeper continental basement. The Galicia Interior Basin is bounded to the east by a major fault located below the continental shelf, and to the west by the Galicia Bank. This basin is part of the Triassic rift system that preceded the opening of the North Atlantic in the Cretaceous (Murillas et al., 1990). It is probably contemporaneous with the formation of the Grand Banks basins off Newfoundland.
Chapter 2
Preliminary Work

2.1 Data Acquisition

The data for the Iberia Seismic Experiment (ISE) were acquired on the R/V Maurice Ewing cruise to offshore Portugal and Spain in July and August of 1997. Both seismic reflection and refraction data were collected, and the ship tracks were carefully planned to complement existing data (see figures 2.1 and 1.1). The acquired data include 4000 km of high quality, multi-channel seismic (MCS) reflection profiles (figure BSMP), as well as 56 ocean bottom seismometer/hydrophone data sets. The MCS data were acquired by the R/V Maurice Ewing using a 160-channel digital streamer and an array of 20 airguns totaling 8400 cu. in. displacement. The shot interval and receiver interval were both 25 m, resulting in a CMP spacing of 12.5 m. A sampling rate of 2 ms was used, with the record lengths ranging from 16 s to 25 s. Bathymetry and magnetic data were also acquired (Sawyer et al., 1999).

A subset of these data, consisting of ISE Line 14, was chosen for use in this research. Figure 2.1 illustrates this line’s location and relationship to the rest of the survey. Line 14 was acquired in three sections, and labeled from East to West accordingly: Line 14E, Line 14M, and Line 14W. Lines 14M and 14W were acquired with the full 4 km streamer, while Line 14E was acquired with only a 1 km streamer due to increased ship traffic near the coast. Geographically, all three sections of Line 14 trend along latitude 41.6 (41° 36’). Line 14E begins with CMP 959 at longitude -9.17303 (9°
Survey Basemap for Vicinity of Line 14

Figure 2.1: This map shows the ISE survey area in greater detail with an emphasis on Line 14. CDP locations are labeled for the three sections of Line 14, with sections 14E and 14M shown in yellow and section 14W shown in green. The same color code as in Figure 1 is used here. Bathymetry is contoured every 500m.

2.2 Review of Preliminary Processing

Conventional processing was used to prepare CMP gathers for demultiple techniques and stacking. Conventional processing was also employed to produce final migrated sections. A synopsis of preliminary processing is discussed below:

2.2.1 Preparation of CMP Gathers

- Bandpass Filter, minimum-phase, 4-8-40-80 Hz

2.2.2 Stacking and Migration

- Kill Noisy Channels
- NMO Correction
- Stack
- Water-Bottom Mute
- Amplitude Correction, spherical-spreading correction, applied on ‘1/distance’ basis with same velocities used for stacking, applied from 0-12 s
- F-K Stolt Migration, 50 Hz maximum frequency, velocity function: 1500 m/s everywhere (constant), velocity scale factor: 110%, Stolt stretch factor: 1
- Amplitude Correction, time-raised-to-power correction, power constant of 3.0, applied from 0-10 s
- Bandpass Filter, minimum-phase, 6-12-24-48 Hz

It should be noted here that the processing described above was applied to Lines 14W and 14M, but not to Line 14E. The Line 14E data were employed exactly as received after a standard processing sequence performed by Dr. Dale Sawyer. More sophisticated processing techniques were not applied to Line 14E because it’s acquisition parameters included only a 1 km streamer length (as opposed to a 4 km streamer length for Lines 14M and 14W). This shorter streamer length resulted in the absence of offset information and thereby precluded the application of more sophisticated processing.

2.3 The Problem of Multiple Reflections in Marine Seismic Operations

The physical conditions that create multiple water-bottom reflections are conceptually simple. First, in the marine environment the air-water interface is a flat, strong reflector, with a reflection coefficient of nearly -1. Second, in most places the water-bottom interface is also a strong reflector. Therefore, we have a non-attenuative medium bounded by two strongly reflecting interfaces - an energy trap (Backus, 1959).

The problem of water-bottom multiples is one of the most ubiquitous and fundamental limitations to the acquisition of marine seismic data (Backus, 1959; Wiggins, 1988). This problem was recognized in the earliest days of seismic exploration, even before the introduction of digital computers into exploration geophysics (Berryhill et. al, 1986; Foster et. al, 1992). The January 1948 issue of Geophysics was dedicated to
articles discussing the characteristics of multiple reflections, and techniques for their
detection (Taner, 1980). Since that time, considerable effort has gone into developing
strategies for their removal (Zhou et. al, 1996).

In the case of the ISE data, a unique set of circumstances allowed coherent, high-
amplitude, multiple energy to persist in the stacked sections. These circumstances also
allowed the multiple energy to be more problematic than it might otherwise be. First, the
aperture width of the receiver array (4 km in the case of Line 14M and Line 14W) was
narrow in proportion to the water depth (at least 3 km in most locations, but increasing to
over 5 km in certain places). This resulted in the angle-of-incidence being generally very
small. The stacking process, like the velocity-discrimination techniques discussed below,
relies upon differential normal-move-out (NMO) between primaries and multiples, and
causes the primaries to stack constructively while the multiples stack destructively.
Because there is a lack of wide-angle information, even at the farthest offsets, this
differential NMO is not able to dominate the stack, and multiple energy persists.
Obviously, this problem is even more severe in Line 14E where a 1 km streamer had to
be used due to ship traffic. Second, in many locations throughout the survey, the travel-
time of the first multiple-sequence was the same or shorter than the travel-times of the
deep-crustal reflections that we wanted to image. Thus, the multiple-sequence completely
obscured relevant deep-crustal structure.

This problem is illustrated in figures 2.2 and 2.3. Figure 2.2 shows a portion of
Line 14M from CMP 1000 to CMP 4000 without any multiple attenuation and in the time
domain. The water-bottom primary reflection arrives at between 4.0 and 4.5 s, while the
Figure 2.2
Line 14 - Mig. and Depth Conv. Sect. - No Mult. Atten.

Figure 2.3
first water-bottom multiple arrives at between 8.0 and 9.0 s and the remaining multiple-sequence obscures everything after this time. Figure 2.3 again shows the same portion of Line 14M without any multiple attenuation, but in this figure the data have been depth-converted in the manner described below. Here the water-bottom primary reflection can be seen to lie at between 3.0 and 3.5 km, while the first water-bottom multiple lies between 10.0 and 14.0 km and again the remaining multiple-sequence obscures everything below this depth. Therefore, in this area of the survey, all features lying at a depth greater than 14 km (and in some places below 10 km) are over-printed with multiple energy. It is this region of the lower-crust that we believe contains the most pertinent structural information regarding the style and sequence of extensional events. Hence, it becomes necessary to attenuate the multiple energy throughout ISE Line 14 before a meaningful structural interpretation can be attempted.
Chapter 3

Multiple Attenuation Methods

3.1 Review of Inside Muting and Weighted Stacking

The first group of demultiple methods to be applied was inside muting and weighted stacking. A range of different inside-mute offset-lengths were tried, with all mutes temporally beginning immediately before the first water-bottom multiple. The experimental offset-lengths ranged from 1 km to 3 km. After examination of the migrated sections produced with the different mutes, it was determined that an offset-length of 2.0 km gave the best results. The maximum offset present in the data is approximately 4 km. A migrated section produced with a 2.0 km inside mute is shown in figure 3.1. For comparison, a migrated section with no multiple attenuation has been included (fig. 2.2).

I tried two types of weighted-stacking functions: linear, with offset multiplied by a slope; and exponential, with offset raised to a power. For linear weighted-stacking schemes, a range of different slopes was tried. The experimental slopes ranged from 2 to 5. Qualitative examination of data stacked with this range of slopes determined the best slope to be 3. Likewise, for exponential weighted-stacking schemes, a range of different exponents was tried. The experimental exponents varied from 1.5 to 3.0. The best exponent was determined to be 1.75, but the quality of multiple attenuation was relatively insensitive to the exponent used. A range of exponents from 1.5 to 2.0 also gave good results. After comparison of the linear scheme yielding the best result (slope = 3) with the exponential scheme yielding the best result (exponent = 1.75), there appears to be virtually no difference in their quality. However, both types of weighted-stacking
Figure 3.1
methods produced higher quality results than the best inside-muting method. A migrated section produced with an exponent of 1.75 is shown in figure 3.2.

There appears to be a threshold for both inside muting and weighted stacking after which the benefit of multiple attenuation is overcome by the degradation of desired primary energy. This threshold allows somewhat better multiple attenuation with weighted stacking than with inside muting.

3.2 Review of Multiple-Model-Trace Subtraction

The second demultiple method to be attempted was multiple-model-trace subtraction. In theory, this procedure is relatively simple; in practice, there are numerous complications involved that make implementation difficult. These complications will be discussed below.

For input, this method used CMP gathers with the preliminary processing already described (fig. 3.3). The CMP gathers were NMO-corrected at multiple velocity rather than primary velocity (fig. 3.4). Next, the CMP gathers were stacked to produce multiple-model-traces (or MMTs). These traces were then repeated to create multiple-model-trace gathers and all amplitudes before the first water-bottom multiple were muted. This produced MMT gathers that theoretically contain only multiple energy (fig. 3.5). Next, the MMT gathers were subtracted from the original CMP gathers that had been NMO corrected at multiple velocity (fig. 3.5 was subtracted from fig. 3.4). This produced a subtracted gather that was still NMO-corrected at multiple velocity (fig. 3.6). The final step before stacking was to remove the NMO-correction at multiple velocity and apply an
Figure 3.2

Line 14 - Migrated Section - Weighted Stack
Line 14 - CMP Gather - NMO Corrected at Mult. Vel.

Figure 3.6

Figure 3.7
NMO-correction at primary velocity to the subtracted gather (fig. 3.7). For comparison, an original CMP gather NMO-corrected at primary velocity (fig. 3.8) has been included. Comparison of figure 3.7 to figure 3.8 shows that the multiple sequence has been substantially attenuated.

Several problems had to be overcome before this method could be implemented. First, the design of the trace-subtraction module in ProMax required that the two traces used in the subtraction be directly adjacent to each other. This meant that instead of individual multiple-model-traces, entire multiple-model-trace gathers had to be created. This created some complications: the fold of the MMT gathers had to replicate the fold of the original CMP gathers; and, offset values had to be created in the MMT headers so that NMO corrections could be applied. Secondly, because only the first multiple in the multiple sequence has an NMO velocity of exactly 1500 m/s, stacking CMP gathers to create MMTs required a time-variant multiple-velocity function, rather than a constant 1500 m/s. Thirdly, ‘index’ header words had to be created to properly sort and merge the MMT gathers with the original CMP gathers before trace subtraction. Finally, the MMTs were much higher in amplitude than the original data traces, and thus a weighting scalar had to be determined through trial and error.

Examination of a migrated section with MMTS applied shows good results (fig. 3.9). Compare figure 3.9 to the migrated section with no multiple attenuation applied (fig. 2.2). However, when MMTS is applied in conjunction with the same weighted-stacking function used above, the results are vastly superior to either the MMTS or the weighted-stacking applied alone (fig. 3.10).

Figure 3.8
Figure 3.10

Line 14 - Migrated Section - MMTS w/ Weighted Stack
3.3 Review of F-K Filtering

F-K filtering was the next demultiple method applied to the data. As described earlier, this technique is based upon velocity discrimination and exploits the differential move-out between multiple reflections and primary reflections. This method employs a 2-D Fourier transform to convert CMP gathers from the traditional t-x domain to the f-k domain after the CMP gathers have been NMO-corrected. A complete f-k filtering scheme includes a specialized NMO-correction followed by an appropriately designed filter. Three different f-k filtering schemes were used for this portion of the research.

The first scheme attempted to attenuate multiples by NMO-correcting CMP gathers at multiple velocity, thereby flattening multiples while leaving primaries with residual move-out (fig. 3.4). This caused the multiple energy to have an apparent-wave-number of approximately zero, while the primary energy had non-zero apparent-wave-numbers. A ‘pie’ filter was then designed in f-k space to reject amplitudes around the f-axis (corresponding to k=0).

The results of this method were generally poor, and primary reflections within both the CMP gathers and final stacked and migrated section were substantially degraded. This degradation was due to the flatness (or zero apparent-wave-number) of primary reflections at near-offsets within the CMP gathers. The primary reflections at near-offsets were attenuated along with the multiple sequence.

The next scheme used a primary-velocity function to flatten primaries while leaving multiples with residual move-out (fig. 3.8). The same ‘pie’ filter as above was
again applied, but this time amplitudes around the f-axis were accepted while amplitudes in all other regions in f-k space were rejected.

The results of this method in the CMP gathers were generally moderate multiple attenuation across all offsets and generally good multiple attenuation at far offsets. In the CMP gathers the primaries were degraded only slightly. The stacked section was high quality but possessed only minimal multiple attenuation. Therefore, a third demultiple scheme was attempted.

The objective of the third scheme was to separate the primaries and multiples into opposite quadrants in f-k space. To do this, a velocity function was required that would over-correct the primaries (giving them a positive apparent-wave-number) and under-correct the multiples (giving them a negative apparent-wave-number). This ‘intermediate’ velocity function was developed and used to NMO-correct the CMP gathers (fig. 3.11). Next, I designed a filter in f-k space to reject most of the negative quadrant, accept the area around the f-axis, and accept the entire positive quadrant. This filter was then applied to the NMO-corrected CMP gathers (fig. 3.12). The ‘intermediate’ NMO-correcting was removed and the gathers were re-corrected using the primary velocity-function. Examination of the CMP gather showed that the f-k filter had left high-frequency artifacts in the data. A bandpass filter with 4-8-24-48Hz corner frequencies was applied to the data before stacking (fig. 3.13). High-amplitude artifacts still persist, however, especially in the first and last traces. F-K filter artifacts aside, the primary reflections are well preserved, the multiple reflections are greatly attenuated at mid-to-far offsets, and the overall data quality is high. A stacked and migrated section was produced
Figure 3.12
Line 14 - Migrated Section - w/ F-K Filter

Figure 3.14
and is shown in figure 3.14. Surprisingly, multiple energy persists throughout the
section. This is most likely due to the persistence of multiple energy at near-offsets in the
CMP gathers. To help overcome this problem, a weighted-stack was performed using the
same weighting scheme as before (weight = offset$^{1.75}$). The results of this stack are shown
in figure 3.15. The f-k filter combined with the weighted stack produced superior results
when compared with the f-k filter alone. However, although examination of figure 3.15
shows the primaries are well preserved and the section generally being high quality, there
appears to be significantly more noise than in figure 3.14.

Finally, f-k filtering was employed in a permutation of all previous demultiple
methods. Specifically, multiple-model-trace subtraction was combined with f-k filtering
and weighted stacking. To accomplish this the best f-k filtering scheme, as described
above, was performed again. But this time subtracted gathers from the previous MMTS
method were used as input, instead of standard data with only preliminary processing. A
CMP gather with both MMTS and f-k filtering applied is shown in figure 3.16. The data
quality of the CMP gather in figure 3.16 is very good except for a few artifacts from the
f-k filtering. After the f-k filtering was performed, the CMP gathers were stacked, again
using the standard weighting scheme. The final stacked and migrated section is shown in
figure 3.17. Examination of the section in figure 3.17 shows very good multiple
attenuation, however the primary reflections are slightly more degraded by noise when
the three methods are combined than when MMTS and weighted stacking are used by
themselves (refer back to fig. 3.10). I believe this is due to the f-k filter introducing noise
into the gathers. This noise could be the result of FFT 'edge effects'.

Figure 3.16
Line 14 - Mig. Sect. - w/ MMTS, F-K Filt. and Wgt. Stk.
In summary, although the combination of MMTS, f-k filtering, and weighted stacking produces a high-quality section, the combination of only MMTS and weighted stacking produces a slightly better section.

3.4 Review of Radon Filtering

The fourth and final velocity-discrimination technique to be applied was Radon filtering. Like F-K filtering, Radon filtering is a type of plane-wave decomposition and therefore segregates the entire wavefield into groups of plane-wave components. However, unlike F-K filtering, Radon filtering does not employ a 2D Fourier transform. It instead uses an array of summation paths across all offsets systematically applied at all time intervals in t-x space to map amplitudes into tau-p space; where ‘tau’ represents time-corrected-for-normal-move-out, or ‘intercept time’; and ‘p’ (in this example) represents the amount of move-out. It should be explained here that in ‘traditional’ Radon filtering, a linear summation path is used (Taner, 1980), in which case Radon filtering is also called ‘slant-stacking’. When slant-stacking is used, ‘p’ refers to the ray parameter in the same fashion as the rest of geophysical literature. There are a variety of summation paths that can be used for the Radon transform; the work performed here employed parabolic summation paths. Because parabolic summation paths were used, ‘p’ refers to the amount of move-out at a reference offset. The objective of the Radon filtering scheme was to create a multiple model in tau-p space that was then inverse-transformed into t-x space and subtracted from the original data to remove the multiple energy.

CMP gathers NMO-corrected at primary velocity (fig. 3.8) were input into the ‘Radon Analysis’ module and transformed into tau-p space. Once in tau-p space, a ‘top-
mute' was designed to mute all amplitudes corresponding to primary energy. This was relatively easy to do because the multiple energy was well segregated into a limited region of Radon space: multiple energy only appeared at later 'tau' values and at larger 'p' (move-out) values. Next, the remaining amplitudes were inverse Radon transformed back into t-x space to create the multiple model (fig. 3.18). This multiple model was then subtracted from the original data (fig. 3.8) to attenuate the multiples (fig. 3.19). Please note excellent attenuation of multiple energy at all locations except the near offsets, where high amplitude energy remains.

This subtractive Radon filter was then applied to all CMP gathers by inserting the 'Radon Filter' module into the 'Stack' flow. After multiple attenuation was performed, the data were stacked and migrated in the same flow using the parameters described above. The resulting migrated section is shown in figure 3.20. After comparison with the migrated section with no demultiple (fig. 2.2), it can be seen that this section exhibits only moderate multiple reduction. However, the underlying primary energy appears to be well preserved and no new noise can be observed in the section.

Next, the same subtractive Radon filter was combined with a 2 km inside mute inside the 'Stack' flow, and again the data were stacked and migrated. The results can be seen in figure 3.21. The combination of these two techniques produced the best results thus far. Examination of figure 3.21 shows extremely effective demultiple and excellent primary preservation.

In summary, the combination of subtractive Radon filtering with inside-muting produced results that where superior to the results obtained from any permutation of
inside-muting, weighted-stacking, MMTS, and F-K filtering. Thus, these data were used as input for further processing and interpretation (see below).
Line 14 - Radon Multiple-Model Gather

Figure 3.18
Line 14 - Radon Subtracted Gather

Figure 3.19
Line 14 - Migrated Section - w/ Radon Filter

Figure 3.20
Line 14 - Mig. Sect. - w/ Radon Filt. and 2KM Mute

Figure 3.21
Chapter 4

Review of Depth Conversion

After demultiple techniques were applied to ISE Line 14 a depth conversion was performed. The first step in creating a depth section was to build a velocity model. To do this, different velocity layers had to be interpreted and the horizons separating these layers had to be defined. Three horizons in the time section were picked to separate four velocity layers:

layer 1: water column
layer 2: unequivocal post-rift sediments
layer 3: combination of syn-rift and earliest post-rift sediments
layer 4: acoustic basement (which likely includes both crystalline rock as well as a thin covering of pre-rift sediments)

The four velocity layers represent a gross simplification of geologic reality. However, the simplicity of the model is appropriate in light of the limited velocity information available to us. Because of the relatively short cable length (4 km) and the relatively deep (up to 5 km) water depth, there is a lack of offset information and thus semblance velocities are unreliable. For this reason, general velocities obtained by previous authors from refraction work (Zelt, 1999; Discovery 215 Working Group, 1998; Whitmarsh et al., 1996) were assumed for the layers. The refraction analysis performed by Zelt (1999) was on a nearby line from the same seismic experiment discussed above (Iberia Seismic
Experiment of 1997). This line is designated 'ISE Line 1' and it's location in relation to ISE Line 14 is shown in figure 2.1.

Next, the 'Volume Viewer/Editor' module was used to import the time horizons and construct a volume of interval-velocities-in-time. The velocity volume for all three sections consisted of a grid with a lateral node-spacing of 50 CMPs, and a temporal node-spacing of 25 ms. The parameters I used to create the velocity volume for Line 14M and Line 14W were as follows:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Velocity at Top (m/s)</th>
<th>Time Gradient (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1800</td>
<td>500</td>
</tr>
<tr>
<td>Layer 3</td>
<td>3000</td>
<td>500</td>
</tr>
<tr>
<td>Layer 4</td>
<td>5000</td>
<td>200</td>
</tr>
</tbody>
</table>

Building the velocity-volume for Line 14E required slightly different parameters. Because layer 2 pinches-out in the landward direction, and the velocities at the top of layer 3 in this region (now the water-bottom) needed to be reasonable, a CMP (lateral) velocity-gradient was necessary within Layer 3. Furthermore, the velocities at the western end of 14E needed to be consistent with 14M. The appropriate CMP velocity-gradient was found through trial-and-error and the final parameters are listed below:
<table>
<thead>
<tr>
<th>Layer</th>
<th>Velocity at Top (m/s)</th>
<th>Time Gradient (m/s²)</th>
<th>CMP Gradient (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>1500</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1800</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1800</td>
<td>500</td>
<td>0.00018</td>
</tr>
<tr>
<td>Layer 4</td>
<td>5000</td>
<td>150</td>
<td>0</td>
</tr>
</tbody>
</table>

As is the case for nearly all velocity-model building, the velocity volume required an application of a smoothing operator. This eliminates sharp boundary-contrasts between layers and prevents the generation of artifacts during depth conversion. The smoothing operator was applied in the same ‘Volume Viewer/Editor’ module that was used to create the velocity volume.

After the velocity volume was complete, the ‘Time/Depth Conversion’ module was used to convert all three of the original time-sections into depth-sections. The maximum frequency of interest was 50 Hz. This module also converted all mutes from time to depth. The three sections after depth conversion are shown in figures 4.1 through 4.3 (Plates 1 and 2).
Chapter 5

Description of ISE Line 14 Seismic Reflection Data

The three sections of ISE Line 14 were examined and the nature of their reflectivity is described without interpretation below. For this purpose, the migrated sections that had already undergone preliminary processing and multiple attenuation (for sections 14M and 14W) as described above were depth converted and displayed with no vertical exaggeration (1:1) in figures 4.1 through 4.3 (Plates 1 and 2).

5.1 ISE Line 14E

Figure 5.1 (Plate 1) shows Line 14E after depth conversion and with no vertical exaggeration. The CDP range for this section is from 959 in the East to 6243 in the West; the depth axis begins at 0 km (or sea-level) and continues to 22 km. There are several through-going themes in the reflectivity of this section.

1) The depth to the water-bottom reflection begins at roughly 0.2 km in the East and steadily increases to the West where a depth of 3 km is reached.

2) Immediately following the water-bottom reflection is a package of stratified reflections of variable thickness that extends across the entire section. The thickness variation ranges from 0.2 km to 4.3 km. The reflections at the top of this package are highly coherent and continuous, although there are intermittent patches of less reflective regions distributed throughout, giving this area a
‘blotchy’ appearance. This top portion reaches a maximum thickness of 1.4 km at the western-most end of the line, but then thins to the east and ultimately pinches-out around CDP 2200. This area is labeled with an A on figure 5.1 (see also figures 5.4 and 5.5). The reflections in the lower portion of the stratified package are only moderately coherent and continuous (as compared with the upper portion), although there is a wider range of coherency and it is likely that this lower portion could be sub-divided further. This area is labeled with a B and can be seen to pinch-out and re-emerge at several locations along the section, with a maximum thickness of 3.0 km at CDP 5100. The reflections in this lower portion at the western end of the section are slightly ‘hummocky’ or ‘diffractive’ in nature, and are only moderately continuous. While in the central part of the section, there are intermittent fingers of both ‘hummocky’ features as well as more stratified, parallel reflectors.

3) Below the package of stratified reflections is a region of low-to-moderately coherent reflectivity. This reflectivity can be described as ‘wormy’ in nature and generally possessing no stratification or preferred orientation in the reflection fabric (labeled with a C on figure 5.1, see also figures 5.4 and 5.5). This area is divided into large, asymmetrical, blocky features, with the corners of these blocks being well defined and protruding into the stratified reflection package above. The tops of these features form the top of acoustic basement, range in depth (below sea-level) from 1.9 km to 6.9 km (becoming incrementally deeper to the West), and dip gently to the East. These blocky features are bounded by relatively high
Figure 5.4: Part of ISE Line 14M shown as a migrated time-section with interpretation. Data are displayed in time and enlarged to illustrate the interpretation of stratigraphic units and basement reflectivity. 'A' corresponds to stratified post-rift sediment; 'B' corresponds to stratified post- and syn-rift sediments, as well as debris material (below the yellow horizon); 'C' corresponds to acoustic basement.
Figure 5.5: Same as Figure 18, but without interpretation. Data are displayed in time and enlarged to illustrate the interpretation of sedimentary units and basement reflectivity.
amplitude reflectors (or groups of related reflectors) dipping strongly (many 45+ degrees) to the West, and are designated alphabetically from AAA to E. Another important observation is that, in some places, the reflectivity near the tops of these blocky features becomes more stratified and somewhat more continuous. These areas of enhanced reflectivity are roughly parallel to the tops of the blocky features.

The entire bottom half of the section is consumed by high-amplitude, coherent noise in the West. This noise layer gradually shallows and consumes almost the entire section in the East.

5.2 ISE Line 14M

Figure 5.2 (Plate 1) shows Line 14M after depth conversion and with no vertical exaggeration. The CDP range for this section is from 836 in the East to 7752 in the West; the depth axis begins at 2 km (below sea-level) and continues to 22 km. Unlike Line 14E, the depth to the water-bottom reflection on Line 14M is relatively constant: from just above 3 km at the eastern edge of the section, then deepening to roughly 3.3 km, and then returning to just above 3 km at the western edge of the section. The same reflectivity themes as observed on Line 14E are also observed here, as well as some new ones.

1) Once again, a package of stratified reflections of variable thickness extends across the entire section. The thickness variation ranges from 0.7 km to 5.4 km. As before, this package is divided into an upper and lower portion for more
convenience in description. The top portion is labeled with an A on figure 5.2 (see also figures 5.4 and 5.5) and again consists of highly coherent and highly continuous parallel reflections. Although overwhelmingly parallel, in some locations the reflections can be seen to terminate into one-another in a variety of configurations. Once again, some areas possess a 'blotchy' appearance. In contrast to Line 14E, this upper region maintains a nearly constant thickness throughout most of the section. It is between 1.0 km and 1.6 km everywhere except a region between CDPs 6900 and 7400, where it thins to 0.7 km. As for the bottom portion, most of the reflections in this region are as coherent and continuous as the upper portion, although there is a substantial degree of variability. This area is labeled with a B and can be seen to pinch-out and re-emerge at certain locations along the section, with a maximum thickness of 4.2 km at CDP 1600. This lower portion again consists of less continuous and less stratified, diffractive reflectivity, as well as highly continuous and highly stratified reflections. However, the vast majority of the reflectivity in the lower portion is classified as the stratified sort. The eastern and central regions of Line 14M only exhibit diffractive reflectivity in isolated areas, while the western region shows a significant layer of diffractive features extending from CDP 5400 to CDP 7200.

2) Underlying the package of stratified reflections is a region of generally low-to-moderately coherent reflectivity (labeled with a C on figure 5.2, see also figures 5.4 and 5.5). The overall reflectivity of this region is much lower in amplitude than the region overlying it. The reflectivity can be described as 'wormy' in
nature and, for the most part, is devoid of any stratification or preferred orientation in the reflection fabric. There are some notable exceptions, however. Like Line 14E, this area is divided into large, asymmetrical, blocky features, but here the corners of these blocks are more rounded, especially in the eastern and central parts of the section. The blocky features in the western segment of Line 14M have corners that are better defined; and the blocks themselves tend to be narrower than in the east, assuming more of a ‘splinter’ shape than a blocky shape. The tops of these features form the top of acoustic basement, vary in depth (below sea-level) from 3.6 km to 8.5 km (with the acoustic basement incrementally shallowing to the West), and dip gently to the East. The blocky features are bounded by relatively high-amplitude reflections (or groups of reflections) that are generally coherent but not necessarily continuous. These reflections (and reflection-groups) dip strongly to the West, although not as strongly as those in Line 14E (25-40 degrees vs. 45+ degrees. Labels F through J designate these reflections. As noted earlier, the reflectivity near the tops of the blocky features is somewhat more stratified and continuous, and is brighter in amplitude, than at other locations in the region.

3) The final noteworthy features in Line 14M consist of relatively high-amplitude, low-frequency, banded reflections located deep in the section (examples are labeled D, E, and F on figure 5.2, see also figures 5.6 and 5.7). Some of these reflection bands exceed 16 km in depth. These features are only moderately more
Figure 5.6: Part of ISE Line 14M shown as a migrated time-section with interpretation. Data are displayed in time and enlarged to illustrate the interpretation of deep basement reflectors. 'F' is believed to represent the Moho; the interpretation of 'D' and 'E' is subjective.
Figure 5.7: Same as Figure 20, but without interpretation. Data are displayed in time and enlarged to illustrate the interpretation of deep basement reflections.
coherent than the background reflectivity, and only intermittently continuous. If these segments are assumed be acoustic expressions of the same continuous features, then these features extend for 20 km or more. Furthermore, the reflection-bands that form these features are roughly 0.5 km in thickness and in places approach 1.0 km. These reflections are roughly horizontal or sub-horizontal, are 'wavy' in certain locations, and appear to interact with the shallower, strongly-dipping reflections described above.

Once again, there is pervasive, high-amplitude noise present deep in Line 14M. However here, this noise is completely non-coherent and is present only locally.

5.3 ISE Line 14W

Line 14W is shown in Figure 5.3 (Plate 2) after depth-conversion with no vertical exaggeration. The section shown here extends from CDP 15231 in the East to CDP 840 in the West, with it's vertical axis beginning at 2 km (below sea-level) and continuing to 22 km. There is substantial variation in the depth to the water-bottom reflection: starting at a depth of 2.9 in the East, abruptly shallowing to 2.2 km at CDP 3200, deepening incrementally to 4.8 km at CDP 7200, and then maintaining a more-or-less constant depth for the remainder of the section and gradually deepening to 5.3 km in the West. Line 14W exhibits all of the features described earlier, as well as some new ones.

1) As before, a package of stratified reflections extends across the entire section, and varies in thickness from pinching-out in one location to 3.2 km in another
location. As mentioned above, reflections throughout this stratified package can be seen to occasionally terminate against one-another in a variety of geometries. Once again, this package is divided into an upper and lower portion for a more concise description. The upper portion (labeled with an A on figure 5.3, see also figures 5.4 and 5.5) consists of parallel reflections of a highly coherent and highly continuous nature. This package pinches-out between CDP 13000 to CDP 13800, and at CDP 9400, but in most places maintains a more-or-less constant thickness of 0.7 km to 0.9 km. This top portion reaches a maximum thickness of 1.0 km in several locations. The bottom portion (labeled with a B) also consists of parallel reflections, but these reflections are not always horizontal, as in the top portion. Although these reflections are more diffractive than in the top portion, they are generally still coherent and continuous. The reflections are highly variable in nature, ranging from highly stratified and continuous to highly diffractive and less continuous; there are also locations where this layer is somewhat transparent. The majority of reflectivity in this bottom portion can again be classified as stratified and continuous. This bottom portion pinches-out and re-emerges at several locations along the line, reaching a maximum thickness of 2.6 km at CDP 12000.

2) The package of stratified reflections overlies a region of generally low-to moderately coherent reflectivity (labeled with a C on figure 5.3, see also figures 5.4 and 5.5). The reflection texture here can be described as 'wormy'. As a whole, the reflections in this region possess very little continuity, and there is no stratification or preferred orientation of the reflection fabric. But once again, there
are some exceptions to the above description. As observed in Lines 14E and 14M, this area is divided into a series of asymmetrical ‘blocky’ features. Unlike the previous lines, however, the size and shape of these blocks are highly variable. These ‘blocky’ features range from large and nearly square, to very small and ‘splinter’ shaped, and generally decrease in size to the West. In the western portion of this line, all of these features are less than 3 km wide. The tops of these features also vary in their dip direction; most of the tops dip back to the East, while a few dip the West. It should also be noted that the tops of these features are dipping somewhat more steeply than their eastern counter-parts. The corners of these blocks are more salient and less rounded than in Line 14M, protruding into the stratified reflection package above. The tops of these features form the top of acoustic basement, vary in depth (below sea-level) from 2.2 km to 7.5 km, and deepen incrementally to the West. However, there are two large regions in the western part of Line 14W where these blocky features are not imaged. These areas extend from CDP 6600 to CDP 4200 and from CDP 2500 to the western end of the line. The blocky features are bounded by relatively high-amplitude reflections (or groups of reflections) that are generally coherent but not necessarily continuous (labeled with letters ‘J’ through ‘V’). Most of these reflections and reflection groups dip to the west, although two exceptions can be observed that dip to the East and are labeled ‘K’ and ‘R’. The westward-dipping reflections dip at between 15 to 40 degrees, somewhat more gently than in Line 14M. The eastward-dipping reflections dip somewhat more steeply (45+ degrees). As noted earlier, the reflectivity near the tops of the blocky features is somewhat
more stratified and continuous, and is brighter in amplitude, than at other locations in the region.

3) Another interesting group of features in Line 14W are the gently-eastward-dipping groups of segmented reflections (labeled with a G). These reflections are nearly horizontal or sub-horizontal (0 to 15 degrees) and in many places appear to be offset by the reflections that bound the ‘blocky’ features described above. These features are relatively high-amplitude, low-frequency, and possess a thick ‘banded’ character. These reflections are only moderately more coherent than the background reflectivity, and only intermittently continuous. Depending on what relationships are assumed between the discontinuous and offset segments imaged in the data, these reflections extend for distances of at least 10 km and probably much more. The deepest of these reflections to be imaged lies at a depth of 16 km, and the broadest of these is imaged as a band of reflectivity at least 0.5 km thick. It should be noted that most of these features are located in the western and central parts of the line, although some of these features are also found in the eastern part.

4) It was mentioned above that there is a region between CDPs 6600 and 4200 that does not contain any of the blocky features described earlier. Instead of blocky features underlying the stratified reflection package, there is a region containing broad, diffractive, ‘hummocky’ reflections. This area is labeled with an H. These features are large, high amplitude, and possess a coherent nature. The lower
portion, on the other hand, is dominated by a ‘hummocky’ texture comprised of very broad, diffractive, parabolic shapes. These shapes tend to be very high-amplitude, but show a large range of variability in their coherency and continuity. Both characteristics tend to decrease westward along Line 14W. The shallowest of these shapes lies at 6.9 km, while the deepest lies at 9.7 km (below sea-level). The maximum depth extent of these features appears to be related in some way to the presence of the dipping reflections discussed in sections 2) and 3).

5) Finally, there is the second region that does not exhibit any of the blocky features discussed in section 2). This region is located between CDP 2500 and the westward extent of the line at CDP 840 and is labeled with an I. The reflectivity in this region shows a ‘wormy’ texture and is moderately coherent and continuous. Reflections within this zone possess a variety of dips and are absent of any preferred orientation. Ostensibly, the reflection fabric within this region may appear to be similar to the region discussed in section 2). Closer examination reveals subtle differences, however. The important contrasts are in this region’s slightly higher coherency, continuity, and amplitude. It should also be noted that the reflectivity of this feature is somewhat more heterogeneous. This region is directly overlain by the stratified reflection package cited in section 1). The top of this region lies at a depth varying from 7.0 km to 7.4 km on it’s eastern side, but then shallows abruptly to the west to a depth of 5.4 km; thus exhibiting a maximum relief of 2 km.
Chapter 6

Interpretation of ISE Line 14 Seismic Reflection Data

The three sections of ISE Line 14 that are described above were examined and the nature of their reflectivity is interpreted in a geologic context below. Again, these sections are displayed with no vertical exaggeration (1:1) in figures 5.1 through 5.3 (Plates 1 and 2) after preliminary processing, multiple attenuation (for sections 14M and 14W), and depth conversion.

6.1 ISE Line 14E

1) The variability in the depth to the water-bottom is interpreted to represent the continental shelf in the East were it lies at roughly 0.2 km depth. Moving westward along the line, the gradual deepening of the water-bottom represents the continental slope. While in the West, the 3 km depth represents the beginning of the Galicia Interior Basin.

2) The unit of stratified reflections immediately following the water-bottom reflection is interpreted to represent the sedimentary package. The general increase in package thickness from East to West is due to the change in setting from the continental shelf to the Galicia Interior Basin. Large local variations in
sedimentary thickness are a result of half-graben structures (discussed below) creating accommodation space that is subsequently in-filled with sedimentary material. The high coherency and continuity at the top of this package (labeled with an A on figure 5.1, Plate 1) implies that the sediment here is highly stratified. However, the existence of small, intermittent regions of less coherent reflectivity within the upper portion creates a blotchy appearance and suggests the presence of less stratified, possibly turbid, sedimentation. The upper portion of this package is interpreted to be purely post-rift in age, and is believed to have been deposited during a period of tectonic quiescence. This is because there is no apparent syn-rift stratigraphy or extensional deformation within this layer. In the lower portion of the sedimentary package (labeled with a B), the merely moderate coherency and continuity of the reflections suggest that the sediments are only moderately stratified. As described above, there is a great deal of variability in this lower portion. In the West, for example, the sediments appear to be poorly stratified. It is therefore inferred that turbid sedimentation and, more especially, debris-type processes played a more important role in the lower portion of the sedimentary package. I believe that the 'hummocky' or 'diffractive' nature of the reflectivity in the western part of this layer implies the presence of a substantial wedge of debris material that is 3.0 km thick in some places. The lower portion is interpreted to be both syn-rift and post-rift in age. This is because some of the stratified sediment is non-horizontal and may have been deformed by rotation of the fault-blocks; and also because the wedges of debris-type material may be syn-rift in age.
3) The region of low-to-moderately coherent reflectivity that underlies the package of stratified reflections is interpreted to be acoustic basement. This region is labeled with an C. The generally ‘wormy’ reflection character of this layer implies that it is composed of mostly igneous material. However, localized areas of moderate stratification are also observed in this layer, as well as places that exhibit a preferred orientation in the reflection-fabric. These features suggest that stratified crystalline material, probably representing metamorphosed pre-rift sediment, is also present. This region is divided into large, asymmetrical, blocky features that are interpreted to be rotated, normal-fault-bounded, crustal blocks. The tops of these fault-blocks dip gently to the East, while the sides are bounded by normal faults that dip steeply (many 45+ degrees) to the West. The fault-blocks are rotated and down-thrown to the West across the normal faults on their western flanks. The tops of these fault-blocks range in depth (below sea-level) from 1.9 km to 6.9 km and become progressively deeper to the West. This deepening trend is inferred to be due to crustal subsidence that results from the progressive-westward stretching and thinning of the crust, as well as increased sedimentary loading in the proximity of the Galicia Interior Basin. It is also worth noting that the shapes of these fault-blocks are very angular, and the tops of the fault-blocks show no rugosity. I infer this to mean that erosional processes did not act upon basement material in a substantive way during the rifting process.
As noted above, the bottom half of the section is consumed by high-amplitude, coherent noise. This noise layer is caused by the first and second water-bottom multiple reflection-sequence. The problem is especially severe in Line 14E because multiple-attenuation techniques, other than CDP stacking, were not applied due to the shorter streamer length. The distortion of the multiple reflection-sequences is because of the depth conversion.

6.2 ISE Line 14M

Line 14M is shown in figure 5.2 (Plate 1). The depth to the water-bottom reflection on Line 14M is relatively constant around 3 km, representing the constant bathymetry of the Galicia Interior Basin.

1) The same unit of stratified reflections that was present on Line 14E is also present on Line 14M. As before, this unit is interpreted to represent the sedimentary package. Although the thickness of this unit is highly variable, once again due to the presence of half-grabens that have been in-filled with sedimentary material, it is generally thicker here than in Line 14E. It is this region of thicker sediment that composes the Galicia Interior Basin. As before, this unit is divided into an upper and lower portion. The upper portion is labeled with an A and is again interpreted to consist of highly stratified sediments. In several areas, close examination reveals down-lap and top-lap relationships between the reflectors. This implies that sedimentation patterns were eustatically driven during periods where the only tectonic activity was subsidence. Once again, intermittent patches of less coherent
reflectivity within the upper portion create a 'blotchy' appearance and suggest the presence of less stratified, potentially turbid, sedimentation. This upper portion is again interpreted to be purely post-rift in age for the same reasons as in Line 14E: the apparent lack of syn-rift stratigraphy and extensional deformation. The lower portion is labeled with a B and, as in Line 14E, is interpreted to be composed of both highly-stratified sediments, as well as poorly-stratified turbid sequences and unstratified debris material; there is generally a substantial degree of variability throughout. However, it should be noted that the lower portion of the sedimentary package in Line 14M is generally more stratified than the lower portion in Line 14E. The same thick wedge of debris material that was expressed in the western part of Line 14E is again imaged in the eastern part of Line 14M. Here it is seen to downlap onto a much smaller debris unit that has in-filled a half-graben structure between CDP 1400 and CDP 2000. Another unit of debris material is imaged in the eastern part of Line 14M between CDP 5400 and CDP 7200. This unit in-fills another half-graben structure and exhibits a more unusual geometry. I believe the unusual geometry of this unit to be the result of the half graben itself changing geometry either during or after sedimentation. It should be concluded that a variety of depositional processes participated in the formation of the lower portion, with no single process dominating. It should furthermore be concluded that the lower portion contains both syn-rift units as well as post-rift units. This is because some of the features exhibit signs of post-depositional deformation, while other features are horizontal or near-horizontal and appear to be undisturbed.
2) Underlying the sedimentary package, and labeled with a C, is the acoustic basement. As in Line 14E, the ‘wormy’ reflectivity present in this region, combined with the general absence of stratified reflections, is interpreted to mean that this layer is composed mostly of igneous material. However, there are some exceptions, especially near the top of this layer. These zones of moderately-stratified reflectivity are again interpreted to be stratified crystalline material, probably metamorphosed pre-rift sediment. The depth (below sea-level) of this layer is variable, ranging from 3.6 km to 8.5 km, but shallows incrementally to the West. I believe this represents the westward progression from the Galicia Interior Basin to the Galicia Bank. Like Line 14E, the basement is divided into rotated, generally large, asymmetrical, fault blocks, but here the corners of these blocks are more rounded and the tops show more rugosity. This is especially true in the central and eastern parts of the section. I infer this to mean that erosional processes were more active in this area. This interpretation is supported by the presence of the thick units of debris material described above. These debris units lie directly adjacent to the erosional area, both to the East and West. In the western part of the section the fault-blocks are more angular, generally much smaller, and do not exhibit evidence of substantive erosion. As in Line 14E, the tops of these fault-blocks dip gently to the East, while the sides are bounded by normal faults that dip steeply to the West, but not as steeply as in Line 14E. The faults here dip at angles between 25 and 40 degrees, rather than 45+ degrees as in
Line 14E. Again, the fault-blocks are rotated and down-thrown to the West across the normal faults on their western flanks.

3) The final significant features to be discussed and interpreted are the high-amplitude, low-frequency, banded reflections located deep in the section and labeled with a D, E, and F. Interpretation of these features is admittedly a matter of conjecture. Furthermore, as stated above, these features are only moderately more coherent than background reflectivity and therefore the original delineation of these structures was necessarily subjective. The deepest reflection-band is interpreted to be the Moho, and is labeled with an F. The Moho is imaged only intermittently throughout the section, and is seen to lie at between 16.0 km and 16.5 km depth (below sea-level). This depth implies a crustal thickness of between 9.0 km and 11.5 km. If the Moho is defined as the velocity boundary between 6.8 km/s and 8.0 km/s, this thickness is generally in agreement with refraction studies that were performed on another ISE line to the north of Line 14 (Zelt et al., 2000). The other two deep reflection-bands in Line 14M are more difficult to interpret with any confidence. These features are labeled with a D and E. The most likely interpretations of this reflectivity are: 1) low-angle detachment surfaces that accommodated early extension; 2) compositional transitions within the crust generally; or more specifically, 3) paleo-Moho that represents the pre-rift or syn-rift Moho that was subsequently isostatically uplifted as the crust thinned. No single interpretation appears to be any better than the others. Finally, it should
be noted that these two reflection-bands appear to cross some of the normal faults described above. Thus, they are inferred to be younger than the faults.

6.3 ISE Line 14W

Line 14W is shown in figure 5.3 (Plate 2). There is substantial variation in the depth to the water-bottom: starting at a depth of 2.9 km in the East, shallowing to 2.2 km at CDP 3200, deepening incrementally to 4.8 km at CDP 7200, and then maintaining an approximately constant depth for the remainder of the section and gradually deepening to 5.3 km in the West. This bathymetry represents the Galicia Interior Basin in the East, progressing westward to the Galicia Bank, then eventually progressing to the Iberia Abyssal Plain in the West.

1) As in the two previous sections of Line 14, there is present in Line 14W a unit of stratified reflections that is interpreted to be the sedimentary package. The thickness of this unit is again highly variable, due to the presence of numerous half-grabens that have been in-filled with sediment. However, the sedimentary package in this section is generally thinner than in the other sections. This is especially true in the eastern part of Line 14W, and this region of thinner sediments is interpreted to represent the Galicia Bank. As before, this unit is divided into an upper and lower portion. The upper portion is labeled with an A and is once again interpreted to consist of highly stratified sediments. As before, close examination reveals down-lap and top-lap relationships between the reflectors. This implies that sedimentation patterns were eustatically driven during
periods were the only tectonic activity was subsidence. Once again, intermittent patches of less coherent reflectivity within the upper portion create a ‘blotchy’ appearance and suggest the presence of less stratified, potentially turbid, sedimentation. This upper portion is again interpreted to be purely post-rift in age for the same reasons as in Line 14E and Line 14M: the apparent lack of syn-rift stratigraphy and extensional deformation. The lower portion is once again interpreted to consist of a variety of sedimentary material, ranging from highly-stratified sediments, to poorly-stratified turbid sequences, to unstratified debris material. This lower portion is labeled with a B. Units of debris material are again observed in many of the half-graben structures in the eastern part of the section, but these debris units are generally much smaller than similar units observed in the other sections. For the most part, sedimentary structures in the lower portion do not exhibit evidence of substantial post-depositional deformation. There is an exception, however, between CDP 6700 and CDP 7900. In this location, it appears that extensional movement along several faults in the underlying graben has severely altered the overlying sediments. It should once again be concluded that a variety of depositional processes participated in the formation of the lower portion, and that the lower portion contains both syn-rift units as well as post-rift units. The latter conclusion is because some features show evidence of post-depositional deformation, while other features are horizontal or near-horizontal and appear to be undisturbed. Finally, it is important to note that the reflectivity of the lower portion assumes a very unusual, relatively transparent character between CDPs 5500 and 6500. The cause of this anomalous reflectivity is not
known. Other authors (Pickup, 1997) have concluded that analogous features in other areas of the Iberia Abyssal Plain are the result of extreme hydrothermal alteration of exposed mantle peridotite. If this is the case, then the relatively transparent part of the lower portion is not part of the sedimentary package at all, but rather peridotite that has been serpentinized by the hydrothermal circulation of seawater. This process may have resulted in the formation of pervasive vertical fractures whose orientation could create a relatively transparent appearance and effectively erase pre-existing reflection fabric. It is reasonable to expect that this hydrothermal circulation may have extended beyond the exposed peridotite and into the overlying sediment, resulting in the weakly coherent stratified reflections that are observed around the relatively transparent region.

2) As in the other sections, the sedimentary package in Line 14W is underlain by acoustic basement. This layer is labeled with a C. As before, the ‘wormy’ reflection texture of this region and the general absence of stratified reflections imply that this layer is composed mostly of igneous material. But again there are some exceptions: zones of moderately-stratified reflectivity, usually near the top of this layer. These zones are interpreted to be stratified crystalline material, probably metamorphosed pre-rift sediment. The depth (below sea-level) of this layer is variable, ranging from 2.2 km t 7.5 km. The top of basement deepens incrementally moving West through the section. This implies that the crust progressively experienced greater subsidence to the West. This was due to progressively greater stretching and thinning to the West, with these episodes of
crustal attenuation finally culminating in the production of oceanic crust believed to lie just West of Line 14W. The basement is again divided into rotated, asymmetrical, fault blocks; but here the size and shape of the fault blocks is much more variable than in the other lines. The fault blocks range from large and nearly square, to very small and 'splinter' shaped and tends to decrease in size to the West. In the western part of this line, the tops of all the fault blocks are less than 3 km wide. The corners of the fault blocks are generally angular in Line 14W, although there are localized areas on some blocks that appear to have been cut and rounded by erosional processes. However, this line does not show evidence of extensive erosion like many of the fault blocks in Line 14M did. The tops of the fault blocks generally dip to the East, but a few dip to the West. It should be noted that the tops of these fault blocks are dipping somewhat more steeply than their eastern counter-parts. This is interpreted to be the result of greater fault-block rotation caused by greater movement along normal faults at their boundaries; and greater down-throw across the normal faults is implied to be the result of greater crustal extension. Thus, the degree of fault-block rotation, fault movement, and crustal subsidence all tend to increase to the West, thereby supporting the above assertion that crustal extension increases in a westerly direction. The normal faults that bound the fault blocks dip mostly to the West (a few dip to the East), and tend to dip more gently here than in Line 14M or Line 14E. Here the westward-dipping faults dip at angles between 15° and 40° (the eastward dipping faults are steeper: 45°+), while the faults in Line 14M dip at angles between 25° and 40°, and the faults in Line 14E dip at angles of 45°+ (see figures 5.1 and 5.2, Plate 1). Finally,
some of the most interesting features of the data are zones where the otherwise ubiquitous fault blocks are completely absent. These zones extend from CDP 6600 to CDP 4200, and from CDP 2500 to the western end of the line. These regions are interpreted to represent areas where there is no crust, and denuded mantle material is directly overlain by the normal sedimentary package (as described above). In addition to the absence of fault blocks, this interpretation is supported by differences in the reflection character observed in these zones. Although the reflection texture in these zones is ‘wormy’ just as it was in the crystalline fault block material, here the reflectivity is lower-frequency, higher-amplitude, and somewhat more coherent.

3) The gently eastward-dipping groups of segmented reflections found deep in the section (labeled ‘G’) are interpreted to be low-angle detachment surfaces that accommodated extension relatively early in the rifting process. The deepest of these detachment faults to be imaged lies at a depth of 16 km, and it is possible that they extend even deeper to the East. As stated earlier, these surfaces are nearly horizontal or sub-horizontal (dipping between 0° and 15°) and in numerous locations appear to be offset by the steeper, westward-dipping, normal faults that bound the rotated fault blocks. The dissection of the eastward-dipping detachment surfaces by the westward-dipping normal faults obviously indicates that the detachment surfaces were the preferred mode of extension early in the rifting process, but were subsequently abandoned at some later time in favor of the block-faulting mode of extension.
4) As mentioned above, there is a region between CDP 6600 and CDP 4200 where the acoustic basement layer is not composed of crustal fault-blocks. This area is labeled with an H. In this region, the sedimentary package is directly underlain by a layer composed of high-amplitude, broadly diffractive, 'hummocky' reflections. These features are interpreted to be mantle material that experienced adiabatic, decompressive melting and was exhumed to the surface during the wholesale unroofing of the mantle. The diffractive, parabolic expression of the reflectivity in this zone is probably due to the plutonic structure this material assumed as it rose toward the surface and was emplaced. The work of other researchers (Louden et al., 1999; ODP Leg 149 Shipboard Scientific Party, 1993; Whitmarsh et al., 1996) documents the omnipresence of serpentinized peridotite throughout the Iberia Abyssal Plain. It is therefore reasonable to expect that this zone is composed of mantle peridotite that has been serpentinized by hydrothermal action. Furthermore, the reflection texture of this zone is noticeably different than the reflection texture of the crustal fault blocks, and thus is probably not composed of the same crystalline material.

5) Finally, there is the second region, located between CDP 2500 and CDP 840, that also does not contain any crustal fault-blocks. This area is labeled with an I. This region does not possess any of the diffractive, parabolic structures discussed above in section 4). However, close examination of the reflection texture in this region shows it to be much more similar to the area discussed in section 4) than
the crustal fault-blocks. Therefore, this area is again interpreted to be composed of unroofed mantle material, more specifically serpentinized peridotite. A maximum relief of almost 2 km is observed in this area, and thus I believe it to be the ‘peridotite ridge’ that has been observed by numerous other researchers (add refs.), and is also observed on several other lines from this experiment. It should be noted that the peridotite ridge appears to have only a very thin (< 0.1 km) layer of sediment overlying it in the far-western extent of the line.
Chapter 7

Producing a Restored Geologic Cross-Section

Next, a geologic reconstruction was produced, beginning with the presently extended state of the Iberia Margin and reversing the rifting process to restore the margin to a presumably unextended state. There are two major reasons for attempting this process. First, the restoration process can be applied in such a way as to impose one or more balancing constraints (see below) upon the cross-section (Dahlstrom, 1969). Requiring a ‘balanced’ cross-section throughout the restoration process helps insure that the reconstructed cross-section is geologically feasible in it’s geometric assertions, and also provides an important check on the feasibility of the initial interpretation of the data (Dahlstrom, 1970; Elliott, 1983). For example, if reversing the movement on a normal fault that was delineated during the interpretation phase is incapable of ‘erasing’ the throw and restoring the fault-block to a presumably undeformed state, then that interpretive delineation can be ruled out. Likewise, if the restored position of a fault-block violates certain geometric criteria in it’s relationship to adjacent blocks, then that particular reconstruction can also be ruled out. It should be noted that, for most geologic scenarios, numerous reconstructions will exist that result in a ‘balanced’ cross-section and are therefore geologically feasible. Thus, simply because a restored cross-section is balanced does not imply that it is indeed the correct reconstruction. However we can say with certainty, so far as our beginning assumptions hold true, that an unbalanced cross-section indicates an incorrect reconstruction. To put it in mathematical terms, the condition of balance in a cross-section is ‘necessary but not sufficient’ to insure that a
reconstruction is correct. Second, restoring the cross-section to a presumably unextended state in a geologically reasonable manner provides important quantitative estimates regarding extensional processes.

7.1 Methodology

Balancing constraints have been employed by geologists in both academia and exploration for many years to accomplish a variety of tasks (Chamberlin, 1910; Chamberlin, 1919; Bally et al., 1966; Hossack, 1979). Numerous balancing methods have been published for enforcing geometric criteria and thereby insuring a balanced cross-section. All of these techniques can generally be classified into one of two families or a combination of both. (1) The first balancing method is the ‘Sinuous-Bed Method’ and was developed by Dahlstrom (1969). The basic thesis of this technique is that bedding horizons, if properly imaged in a deformed state, will maintain the same length after being unfaulted, unfolded, and restored to an undeformed state. In the case of faulting it is implied that the unrestored horizon is segmented and that reconstruction reconnects all segments into a continuous surface. (2) Another method, developed by Gwinn (1970), is called the ‘Equal-Area Method’. As it’s name implies, this technique states that the cross-sectional area of the entire section, as well as each individual unit within the section, should be the same both before and after the reconstruction process. This method is often used in concert with the sinuous-bed method to constrain bed thicknesses where seismic and well data are sparse.

Several assumptions are inherent in these balancing constraints. First, there is the obvious assumption that all strain is plane strain. In other words, material has neither
entered nor exited the plane of the cross-section during deformation. This assumption is
impossible to validate. At the very least however, arranging a cross-section so that it’s
surface trace is parallel to the direction of tectonic transport is an essential measure
towards allowing this assumption to be true (Boyer et al., 1983). Other assumptions
include the absence of pressure solution mechanisms (Woodward et al., 1986) and
tectonic compaction (Hossack, 1979). Because the Iberia Margin is an extensional
margin, these last two assumptions can probably be considered irrelevant.

Determining what balancing method to employ for this research and how to apply
it created some interesting challenges. First of all, examples in the literature of both line-
balancing and area-balancing methods rely heavily upon the presence of copious amounts
of pre-deformational (in the case of Iberia, pre-extensional) sedimentary units. As noted
above, nowhere in the Line 14 data is any substantive pre-rift sediment observed; and
where small amounts are observed, it is imaged only intermittently. This therefore
precludes the use of equal-area methods. The use of sinuous-bed methods is severely
restricted because there is only one pre-rift bedding horizon present in the data: the top of
acoustic basement. Thus, the only available opportunity to apply a balancing criterion to
the data was to apply a line-balancing method to the top of basement. This relatively
straightforward restoration scheme was complicated by the presence of substantial syn
and post-rift erosion of the basement surface. The situation becomes more ambiguous
when the presence of pre-rift erosion, and pre-rift basement topography in general, is
considered. At locations where the tops of the fault-blocks are relatively planar and their
corners are relatively angular, the line-balance criterion was easy to enforce. Conversely,
at locations where the tops of the fault-blocks are rugose and their corners are rounded, this balancing technique becomes somewhat ambiguous and subjective.

This balancing method was put into practice by first digitizing each fault-block imaged on Line 14 as a rough polygon. This was performed using Kingdom Software by Seismic Micro Technology. Interpretation of the Line 14 seismic data delineated 40 separate fault-blocks; thus 40 polygons were digitized. The tops of the fault-blocks formed the tops of the polygons; the normal-faults that bounded each fault block on both sides formed the sides of the polygons. The bottoms of the polygons were drawn arbitrarily by drawing a straight line connecting the bottom of each adjacent fault. This was done to close each polygon and prevent visual confusion during the reconstruction process. In addition to digitizing the fault-blocks, the deep, low-angle reflectors were also digitized and tied to their corresponding fault-blocks. These deep reflectors are described above and can be observed in figure 5.3 (Plate 2), labeled with a G. However, inferring which fault-block each reflector should be tied to was occasionally subjective. Each of the 40 polygons, as well as the deep reflectors, are shown in their unrestored positions in Figure 7.1 (Plate 1). In this figure, the three segments of Line 14 were connected at the tie points described above, and the horizontal scale was converted from CDPs to kilometers. The zero point on the new kilometer scale is located at the first (easternmost) CDP on Line 14E (CDP 959).

The polygons were then output from Kingdom Software and their formats were slightly modified. Next, the resulting data files were input to an in-house software package authored by Dr. Dale Sawyer, and each of the 40 fault-blocks were restored to their inferred pre-extensional configuration. This process involved a degree of
subjectivity; however, the restoration sought to optimize certain objective constrains on
the fit between adjacent fault-blocks. These constraints included: 1) The geometry of the
normal-faults bounding the fault-blocks. The translation and rotation used to reconstruct
the initial position of adjacent fault-blocks should not contradict the motion allowed by
the faults. Because of the assumptions described above, reconstructed relative motion
should not allow adjacent fault-blocks to produce either overlap or a void. This would
result in either a mass surplus or a mass deficit, respectively. 2) Because this
reconstruction applied the sinuous-bed method to the top of acoustic basement, it was
necessary that the (pre-extensional) top of acoustic basement should form a relatively
horizontal surface after restoration. The pre-extensional tops of the fault-blocks were
moved into coincidence with a horizontal line at 0 km depth (figure 7.1, Plate 1) during
restoration. This line is purely arbitrary and is not meant to imply that subsidence studies
were conducted. As explained above, the presence of presumably erosional rugosity on
the basement surface resulted in difficulty in the enforcement of this criterion. Namely, it
was necessary to imply which parts of the basement surface were eroded and which parts
were ‘original’. Because most of the normal-faults are westward-dipping, most of the
fault-blocks have been rotated clockwise. This means that the westward corners of these
fault-blocks were rotated upward, while the eastward corners were rotated downward.
Thus, the assumptions are made that the western corners experienced more erosion, and
that the eastward corners experienced less erosion. Therefore, the basement surface near
the eastern corner of each fault block was given greater deference throughout the
restoration process. In regions where basement rugosity was so pervasive that criterion
(2) could not be applied, criterion (1) was relied upon solely. Throughout this process, the
deep, low-angle reflectors are translated and rotated commensurately with their associated fault-blocks.

7.2 Results

The restored section is shown in figure 7.1 (bottom) (Plate 1). The results of the reconstruction are encouraging because requirements (1) and (2), explained above, generally do not contradict each other. There are, however, a few locations where space problems exist (i.e. overlaps and voids). This is especially true where back-dipping (east-dipping) normal-faults are present; these situations resulted in a mass surplus at depth. A rather substantial void is observed at roughly 180 km along the line. This is due to erosion of the fault surface on the foot-wall. Because the foot-wall was removed it was not possible to use criterion (1) above in matching the hanging-wall. Thus criterion (2) was applied solely and the westward block was matched against the extrapolated fault. Another interesting result is that the deep, low-angle reflectors generally tend to line up during the restoration process, although there are several exceptions.

Throughout the restoration process, the software recorded detailed information about the movements required to put the fault-blocks in their proper locations. Geologic parameters, such as fault-block rotation and strain measurements, were derived from this data. Certain key parameters are illustrated in figures 7.2 through 7.5.

A plot of Block Rotation vs. Restored Distance is shown in figure 7.2. The amount of block rotation about the centroid of each polygon was calculated for all 40 blocks and this value was plotted as a point. Positive values of block rotation refer to clockwise rotation during restoration or counter-clockwise rotation during extension. This
is the typical direction for a down-to-the-east listric fault. Therefore, negative values of
block rotation correspond to down-to-the-west listric faults. As expected, nearly all points
lie in negative space. Although this plot shows a great deal of scatter, there are some
discernable trends. First, variability in the rotation values steadily decreases eastward. In
the western part of Line 14, rotation values range from -30° to +15°, while in the eastern
part, values range from -20° to -5°. Second, if the positive block rotation values (and
therefore the eastward-dipping listric faults, or antithetic faults) are ignored, it is observed
that the absolute value of block rotation tends to decrease eastward, although this trend is
very weak. This implies that crustal extension tends to increase westward.

Figure 7.3 shows a plot of the Extension Factor (β) vs. Restored Distance. For this
calculation, the horizontal distance between the centroids of two adjacent blocks was
recorded both before and after restoration. The unrestored horizontal distance was then
divided by the restored horizontal distance to yield β. Because each calculation was
performed on two adjacent blocks, the resulting β value is effectively the average strain
across a two-block distance, although this distance is variable due to variable block
dimensions. Thus figure 7.3 includes 39 data points corresponding to the 39 adjacent
block pairs. Once again, there is a great deal of scatter in this data; but there are also
some notable features. First, at approximately 110 km restored distance, there is an
outlying data point with a very large β of roughly 10.4. This corresponds to the block pair
that encompasses the large region of presumably exposed mantle peridotite imaged in
Line 14W (figure 5.3, labeled with an E). Excluding this statistical outlier, β ranges from
1 to 3, with most values ranging from 1 to 2. Finally, β tends to decrease eastwardly,
although the trend is again weak.
Figure 7.2: Plot of Block Rotation vs. Restored Distance for each of the 40 crustal fault-blocks imaged on Line 14. Negative block rotation designates down-to-the-west faulting. The 'zero' of the horizontal axis is tied to the first CDP of Line 14W (CDP 840).
Figure 7.3: Plot of Beta (extension factor) vs. Restored Distance. Beta has been averaged across two adjacent blocks at each location. The 'zero' of the horizontal axis is tied to the first CDP of Line 14W (CDP 840).
The averaging effect described above was expanded from measuring strain across two-block intervals to six-block intervals in figure 7.4. As before, the horizontal distance between the centroids of blocks spaced an interval of six apart was recorded both before and after restoration. The unrestored horizontal distance was then divided by the restored horizontal distance to give an average $\beta$. Figure 7.4 shows 35 data points representing $\beta$ values across six-block intervals. This figure shows considerably less scatter than its predecessor. But now there is a cluster of 5 outliers representing the 5 six-block intervals that span the region of exposed peridotite discussed above. This cluster possesses a $\beta$ of about 5. Excluding this cluster, there is a discernable trend of $\beta$ decreasing eastward, with all points ranging between 1 and 2.

Figure 7.5 is the same as figures 7.3 and 7.4, but here the strain is calculated across a ten-block interval, creating 31 data points. The ten-block averaging effect produces a strong trend, with the exception of the same cluster of outliers as in figure 7.4. In this figure, $\beta$ smoothly decreases eastward after 150 km, ranging between 1.0 and 1.5.

If the process of calculating $\beta$ with increasing block-intervals were continued here, the reader would see all data points converging to the average strain value for the entire line, which is the equivalent of a forty-block interval. This average strain value is $\beta=1.46$. Thus, the average extension expressed by the present-day structures imaged in this experiment across all of Line 14 is equal to 46%.
Figure 7.4: Plot of Beta (extension factor) vs. Restored Distance. Beta has been averaged across six adjacent blocks at each location. The 'zero' of the horizontal axis is tied to the first CDP of Line 14W (CDP 840).
Figure 7.5: Plot of Beta (extension factor) vs. Restored Distance. Beta has been averaged across ten adjacent blocks at each location. The 'zero' of the horizontal axis is tied to the first CDP of Line 14W (CDP 840).
Chapter 8

Construction of a Crustal Thickness Model

Information obtained through this research and the work of others regarding crustal thicknesses in this area, although sparse, was used to construct a 2D crustal thickness model for Line 14. Available crustal-thickness data were combined to produce a model that was faithful to observed crustal features while at the same time avoiding assumptions of additional structural complexities that are not observed by existing data. Thus, an effort was made to create a ‘minimum structure’ model.

Figure 8.1 shows the minimum-structure crustal-thickness model constructed from available data. The same unrestored fault-block polygons and deep, low-angle reflectors are shown here as in figure 7.1. The semi-continuous line crossing the model below the polygons is the presumed base of the crust or inferred Moho. For this model, the assumed thickness of non-attenuated crust is 35 km. This number was chosen because it is roughly the world-wide norm for undeformed continental crust; and previous investigations, as well as the geologic context, of the Iberia Peninsula do not indicate any abnormalities regarding it’s crustal thickness. Therefore, the crustal thickness at 0 km in figure 8.1 (the eastern end of Line 14E, CDP 959) was set at 35 km. Because no fault blocks were imaged at this immediate location, the top of the crust was set at 0 km depth and thus the bottom lies at 35 km depth. The assumption that non-attenuated crust lies below this point is no doubt in error because extensional features have been reported on land many kilometers east of here. Hence, our inference most likely errs by over-estimating crustal thickness. This was intentional and is explained below.
Figure 8.1: (Top) Results of Zelt et al. (2000) seismic travel-time inversion of both OBS and MCS data for ISE Line 1. Green horizon is bathymetry; upper black horizon is the top of acoustic basement; lower black horizon is the Moho and this horizon is also projected onto the bottom figure. (Bottom) Minimum-structure model of crustal thickness for ISE Line 14. Fault-block polygons and deep reflectors are shown as before, the lower black horizon is the inferred Moho. Values for crustal thickness are derived from the results of this research, the results of Zelt et al. (2000), and others (Louden et al., 1999; Whitmarsh et al., 1996). The red horizon is the same Moho as the top figure, projected onto ISE Line 14 for comparison. For this projection, the horizontal location of the 'peridotite-ridge' basement feature (marked with a 'p') on both lines was aligned. All values are in kilometers with a 2:1 vertical exaggeration.
We believe that the seismic imaging efforts performed as part of this research have enabled us to directly observe the Moho on Line 14M. The feature interpreted as the Moho is labeled with an F in figure 5.2, and lies at between 16.0 and 16.5 km depth, corresponding to a crustal thickness of 10 to 12 km. This agrees well with the tomography work of Zelt et al. (2000) on another Iberia Seismic Experiment line to the north, which gave a crustal thickness of 12 to 14 km for this area. Therefore, we are confident in this value. This feature is imaged on Line 14M between CDP 980 and CDP 6215, corresponding to between 67 km and 132 km, and is likewise included in the minimum-structure model in figure 8.1.

The next feature we wish to include in the minimum-structure model is the local maxima in crustal thickness related to the local high in basement topography that defines the Galicia Bank (figure 1.1). Because the Moho was not directly imaged in this area, the work of Zelt et al. (2000) was again relied upon. The maximum crustal thickness derived for the Galicia Bank area from Zelt's investigation was inferred to be a roughly appropriate analog for the Galicia Bank on Line 14. This provides a value of 16 km. Thus the maximum crustal thickness below the Galicia Bank on the minimum-structure model was set to 16 km. The lateral position of this point was set, somewhat arbitrarily, below the local high in basement topography located at 167 km (figure 8.1).

The nature of the crust within the ocean-continent transition (OCT) of the Iberia margin is well documented by the work of other authors (Louden et al., 1999; Whitmarsh et al., 1996). These authors concur that crustal thicknesses here range from 2 km to 5 km, although at some locations in the OCT, basement material apparently consists of serpentinized peridotite with no observable crust. On Line 14, everything west of 251 km
is interpreted to be the OCT. Therefore, on the minimum-structure model the crust is set to 5 km thick at 251 km horizontal distance. At other locations in the OCT where fault-blocks are present, the crustal thickness is likewise set to 5 km. This includes an ‘island’ of fault blocks between 280 km and 301 km that is interpreted to be surrounded by mantle peridotite (see figure 5.3, Plate 2).

The regions presumably consisting of exposed mantle peridotite on Line 14W (figure 5.3, labeled with ‘E’ and ‘F’, Plate 2) are included in the model and shown in figure 8.1 as areas where no crust is present. These areas can be seen to extend from 251 km to 280 km, and from 301 km to the western end of the line.
Chapter 9

Conclusions

The minimum-structure crustal thickness model described above results in an average crustal thickness of 9.9 km for the part of the line spanning from the eastern end at 0 km, to the fault-block designated ‘40’ and inferred to be the westernmost crustal material at 301 km (figure 8.1). The model, no doubt, contains large errors; and thus the average crustal thickness value contains large errors. However, as noted above, an attempt was made to insure that errors were over-estimations rather than under-estimations in crustal thickness. For this reason, we regard the 9.9 km thickness an over-estimation.

Our examination and analysis of faults and inferred fault-block motions observed in the data has yielded an extension factor (β) of 1.46. Now let us enumerate several assumptions: 1) the thickness of the non-attenuated crust prior to extension was 35 km 2) throughout the entire extensional process only the ‘pure shear’ mode of extension (add a ref.) was relevant 3) all extension experienced by this region throughout the rifting process is recorded in the present positions of the fault-blocks and that the motion of these fault-blocks was controlled by the faults we observe. If all these assumptions are correct, then a β of 1.46 should result in a 35 km thick crust being thinned to an average thickness of 24 km. However we observe an average thickness of 9.9 km. Even after acknowledging the great uncertainty in our model, a substantial discrepancy is obvious. If the initial crustal thickness were assumed to be the only invalid assumption, an initial thickness of 14.5 km would be required to explain the present-day average thickness of
9.9 km. This requirement is grossly unreasonable. Perhaps the invalid assumption is that all crustal extension is reflected in presently observable faults. If it is true that 35 km thick crust has been thinned to 9.9 km, then a $\beta$ of 3.54 is required. While this is more feasible than the previous result, it is still unsatisfying. Finally we consider the validity of the pure shear assumption. Perhaps extensional modes other than pure shear were active during rifting, and crustal material has been removed from the plane of Line 14. This explanation seems to be more attractive.

If we decide to logically pursue the explanation of crust being removed from the plane of Line 14, the next requirement is to find a viable place or places for it to have gone. The accountancy of continental crust does not provide the same luxuries that the accountancy of oceanic crust provides. There are no subduction zones or mid-ocean-ridges to create 'fudge factors' that help reconcile the crustal balance-sheet. If crust has been removed from one place on the earth's surface it should be found in another place on the earth's surface (usually). First we'll examine the likelihood of the missing crust moving either north or south of Line 14. It is very unlikely that crust moved to the north. This is because an examination of Line 1, to the north, shows a similar amount of faulting and fault motion; and it likely possesses a similar extension factor. However, we are reasonably certain that the crust there is no thicker than our model for Line 14, because our Line 14 model is, in part, derived from the tomography investigation performed there. It is also very unlikely that the missing crust moved to the south. This is because the OCT widens substantially moving southward along the Iberia margin; and south of Line 14 the Galicia Bank and Galicia Interior Basin are replaced by the Iberia Abyssal Plain (figure 1.1). As stated above, the OCT is known to consist of very thin crust, and in some places
no crust at all. This leaves us only to look westward for the missing crust. I believe that this is the most appealing solution. The ‘simple shear’ mode of extension (Wernicke, 1985) could have been active during some or all of this margin’s evolution. The asymmetrical extensional style of simple shear would cause one side of the rift to be deficient of crust after final breakup (figures 9.1 and 9.2). This would mean that the missing crust could be found at Iberia’s conjugate margin across the Atlantic: the Grand Bank of Newfoundland. In summary, the only good explanations for the apparent lack of crust are: that we are only able to observe evidence of a portion of the total extension that has occurred along Line 14; that crust has been removed to the Newfoundland side by some type of asymmetrical extension, such as simple shear; or some combination thereof.
Figure 9.1: Models of end-member strain geometry in rifts. (a) In the 'Pure-shear' model, crust and mantle lithosphere are attenuated uniformly along any given vertical reference line. (b) In the 'Simple-shear' model, relative extension of crust and mantle lithosphere along vertical reference lines is nonuniform. Taken from Wernicke, 1985.
Figure 9.2: Wernicke's (1985) classic model: 'Hypothetical normal simple shear of the entire lithosphere'. Possible geometries are variable. However, any normally sheared lithosphere can be divided into five zones that correspond to the relative thinning of the crust as compared to the thinning of the mantle lithosphere.
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ISE Line 14E

Figure 4.1: ISE Line 14E shown without migrated and depth-converted and are exaggeration (1:1 section). AGC has also
Figure 5.1: ISE Line 14E shown with interpretation. Data have been migrated and depth-converted and are displayed without vertical exaggeration (1:1 section). AGC has also been applied.

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Figure 4.1: ISE Line 14E shown without interpretation. Data have been migrated and depth-converted and are displayed without vertical exaggeration (1:1 section). AGC has also been applied.
Figure 4.2: ISE Line 14M shown without interpretation. Data have been migrated and depth-converted and are displayed without vertical exaggeration (1:1 section). AGC has also been applied.
Figure 7.1: Unrestored (top) and restored (bottom) crustal fault-block layers with vertical exaggeration. The zero point on the horizontal scale is tied to a specific reference point, and the blocks are arbitrary and are included solely to close the polygons. The blocks are translated commensurately with the associated blocks during the restoration process.
restored (bottom) crustal fault-blocks. Both horizontal and vertical scales are in km; there is no point on the horizontal scale is tied to the first CDP on Line 14E (CDP 959). The bottoms of the steps solely to close the polygons and aid visual interpretation. Deep reflectors were rotated with the associated blocks during restoration and are included in this figure.
Figure 4.1: ISE Line 14E shown without interpretation. Data have been migrated and depth-converted and are displayed without vertical exaggeration (1:1 section). AGC has also been applied.
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Figure 5.3: ISE Line 14W shown with interpretation. Data have been migrated and depth-converted and are displayed without vertical exaggeration (1:1 section). AGC has also been applied.

ISE Line 14W

Figure 4.3: ISE Line 14W shown without interpretation. Data have been migrated and depth-converted and are displayed without vertical exaggeration (1:1 section). AGC has also been applied.
Data have been applied without vertical application.