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DEEP STRUCTURE OF THE FORELAND TO THE CALEDONIAN OROGEN, NW SCOTLAND: RESULTS OF THE BIRPS WINCH PROFILE

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Abstract. The WINCH marine deep seismic reflection profile crosses the Hebridean shelf, the Proterozoic foreland to the Caledonian orogen, west of Scotland. The data quality is very good. The upper crust is largely devoid of coherent seismic reflections, although this may in part be due to acquisition techniques being inappropriate for this problem. In contrast, the middle and lower crust (10-25 km depth) exhibits good reflections; the mid crust contains reflectors which may be relics of early Palaeozoic, Caledonian (or earlier Grenvillian) eastward-dipping thrust zones, which pass into an acoustically strongly layered lower crust. The Outer Isles Thrust is mapped from the surface to the mid crust, and tied into its land outcrop on north Lewis. Reactivation of this thrust offshore, in a normal sense, in Mesozoic times caused the formation of the Minch and North Lewis Basins. The Moho is defined by a strong band of reflections at about 27 km depth, which correlates well with results from the HMSE explosion seismic survey. Moho depth is apparently rather uniform in the area of the foreland crossed by WINCH. WINCH and HMSE results together suggest a mean crustal velocity for the Hebridean shelf of $6.4+0.1$ km s^{-1}. The eastward-dipping Flannan Thrust can be mapped into the upper mantle on three lines from about 15 to 45 km depth, well into the upper mantle. Neither the Flannan Thrust nor the Outer Isles Thrust appear to pass straight through the reflective lower crust, suggesting that the lower crust is a region of high strain. The Outer Hebrides is a positive block probably formed as an isostatic response to Mesozoic normal faulting which reactivated the Outer Isles Thrust.

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INTRODUCTION

The Western Isles-North Channel (WINCH) deep crustal seismic reflection profile was recorded for BIRPS (British Institutions' Reflection Profiling Syndicate) at sea along the west coast of Britain [Brewer et al., 1983]. Its purpose was to study crustal and upper mantle structure of the Caledonian foreland and orogen. This paper reports the results from the foreland, offshore west Scotland, where data quality is very good, structures observed are apparently rather simple, and reflections are obtained from deep into the upper mantle. The WINCH profile extends the results of an earlier traverse, MOIST [Smythe et al., 1982, Brewer and Smythe, 1984], which was a highly successful test of the technique of deep crustal reflection profiling in British waters.

WINCH was recorded for BIRPS by the

Geophysical Company of Norway (GECO). An extended airgun array (180 m long) towed at 8 m depth was used, with a total volume of 4795 in^3, operated at a pressure of about 2000 psi, which delivered about 120 bar m. Data were recorded to 15 s with a 60 channel streamer approximately 3 km long towed at 15 m depth. Station spacing was 50 m and sampling interval 4 ms. The data were processed by GECO in close consultation with BIRPS, using conventional industry processing. Deep reflections were enhanced by the use of the extended source in conjunction with receiver array simulation, although this adversely affected the resolution of shallow (<2 s) reflections.

The data, stacked 30-fold, are available at cost of reproduction from the Head of Marine Operations Research Programme, British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, United Kingdom.

The data illustrated in this paper are unmigrated. However, in conducting interpretations of key areas simple hand migrations were carried out. Furthermore, Shell Expro UK supplied experimental migrations of certain areas. Although we are confident about the general conclusions we present, careful detailed modelling may well refine details [cf. Peddy, 1984].

REGIONAL GEOLOGY

WINCH and MOIST describe a complete traverse running from the western margin of the Caledonian orogen along the north coast of Scotland into the foreland west and south of the Outer Hebrides (Figure 1). The traverse crosses the boundary of the orogen again off the SW coast of Scotland near the island of Islay, although here structural relationships are less well understood than those along the north coast of Scotland.

The Caledonian foreland is a complex of gneisses and granulites incorporating metasediments, metavolcanics and metamorphosed layered basic and anorthositic bodies, with various granites and pegmatites that constitute Lewisian basement rocks (see Watson [1975] for a review). Most of these rocks were in existence during a period of regional gneiss-forming metamorphism which ended about 2700 Ma (the Scourian deformation). The earliest recognizable structures (ductile shear zones, sometimes associated with gravity anomalies), generally characterized by a NNE grain, were established before the end of this episode. Tectonic and metamorphic activity continued intermittently until about 1600 Ma. The later phases, the Laxfordian deformation, created narrow NW-SE zones of strong deformation between blocks, within which pre-Laxfordian features are less severely modified. Granites and pegmatites were emplaced ubiquitously during the late stages of Laxfordian activity, accompanied by retrogression to amphibolite facies of granulites formed in earlier Laxfordian or Scourian episodes.

The Caledonian foreland is bounded to the west by the passive continental margin of the Rockall Trough (Figure 1), a major rift formed during the early phases of opening of the North Atlantic. To the east of the foreland lies the Caledonian orogen. On land, the orogenic front is defined by the Moine Thrust zone. Proterozoic metasediments (originally mainly shallow marine or lacustrine sands or shales) of the Moine succession lie above this zone, and moved westward over the foreland an unknown distance during late episodes of the Caledonian orogeny (i.e., in Siluro-Devonian times; see the discussions in Watson and Dunning [1979] and Brewer and Smythe [1984]. The foreland was apparently only little affected by the Caledonian orogeny. One major structure, which was compiled and named the Outer Isles Thrust by Dearnley [1962]; aka Outer Hebrides Fault; Sibson [1975, 1977] is subparallel to the Moine Thrust, and therefore assumed to be of Caledonian age, although it can only be said with certainty to be post-Laxfordian. The rocks of the Caledonian orogen lie outside the region of WINCH discussed in this paper, and will not be dealt with further.

After the Caledonian orogeny the areas of the orogen and foreland which now lie offshore were subject to extension associated with the opening of the North Atlantic. Basins, for example, the Flannan Trough and Minch Basin, were filled with Permo-Triassic and younger sediments. The general trend of these basins shows that their structure was controlled by the underlying Caledonian framework [Naylor and Shannon, 1982, pp.103-114]. The MOIST profile shows in detail that many of these basins formed by extensional reactivation of Caledonian thrusts [Smythe et al., 1982]. In many areas, though, the sedimentary rocks in the deepest parts of the basins are undated, and it is possible that some of the basins are immediately

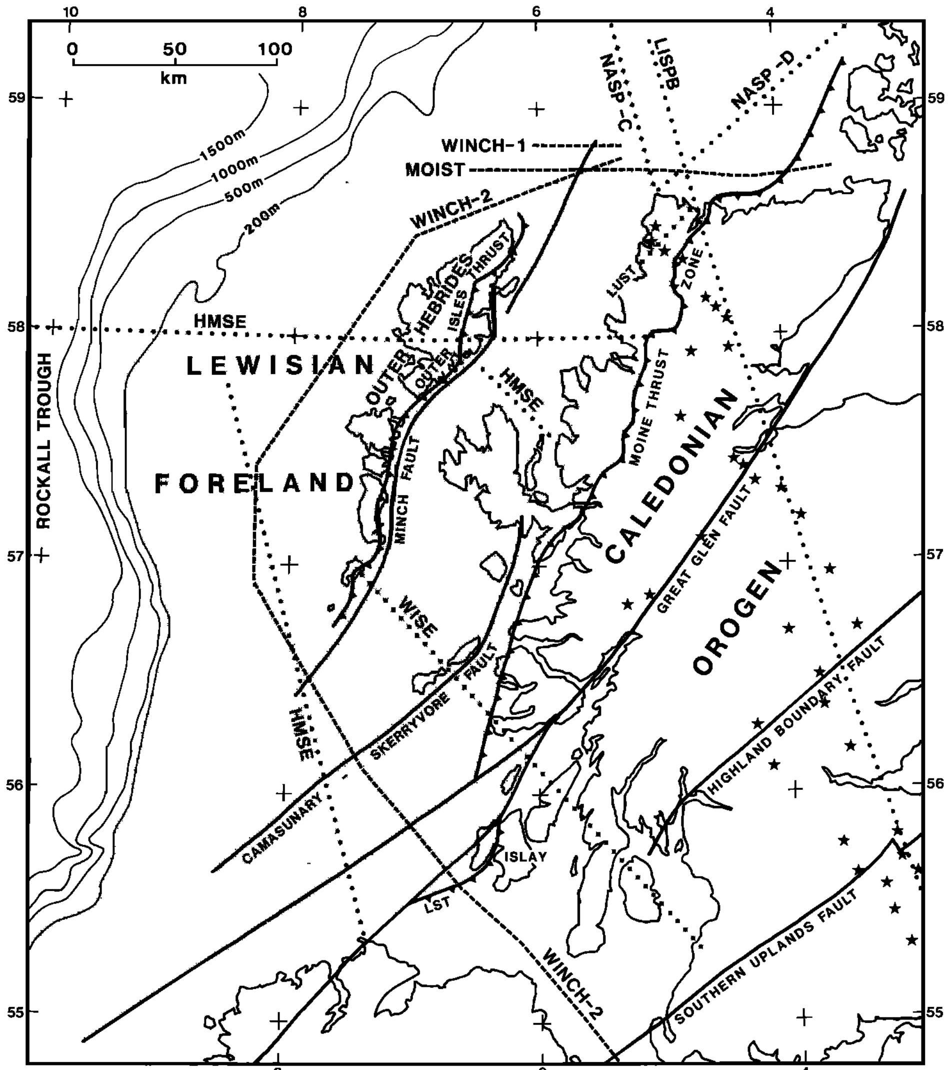

Fig. 1. Location of deep seismic profiles MOIST and WINCH (dashed lines) in relation to the Caledonian orogen, foreland, and the passive continental margin of Rockall Trough to the west. Major faults are shown as solid lines. Dotted lines show locations of explosion crustal refraction profiles NASP, LUST, LISPB, HMSE (discussed in text) and WISE (unpublished). Stars show sites of the conductivity traverse parallel to LISPB [Hutton et al., 1980]. LST is Loch Skerrols Thrust.

postorogenic (i.e., Devonian) in age, and conceivably as old as Torridonian (c. 1000 Ma).

OTHER GEOPHYSICAL STUDIES

Northern Scotland and the Scottish continental shelf have been the subject of many seismic studies on both regional and local scales, partly because of the extensive exposures of Precambrian basement, and the opportunity it allows to study rocks from deep within the crust. The regional studies have proved useful for locating the Moho, the crust-mantle boundary, whereas the local studies show velocity variations in the upper part of the crust possibly explicable in terms of varying basement geology. The structure of the mid-crust, in particular along the boundary zone of the orogen, is not, however, well understood.

The LISPB regional refraction profile (Figure 1; Bamford et al. [1978] was recorded to study the British Caledonides along a north-south traverse. While it provided good quality data on the structure of the orogen, interpretations of data from the foreland are rather uncertain, because they depend mainly on sparse data recorded from a single shot at sea off the north coast of Scotland. Initial interpretation of the data (by travel-time modelling) suggested a division of the crust of northern Britain into three layers: an upper crustal layer with velocities of 6.1-6.2 km s^{-1}, a mid-crustal layer with velocities of 6.4-6.5 km s^{-1}, and a lower crustal layer with velocities of about 7 km s^{-1}, overlying a Moho at 27-28 km depth in the foreland, and gradually deepening to the south. This interpretation has been refined by Cassell [1982] (B.R. Cassell, personal communication, 1983) by modelling the amplitudes of the phases and assuming laterally variable layering. It appears that although this three-layer model is appropriate for the orogen, the boundary between the middle and lower layer probably does not exist under the foreland (where data density is particularly low). Instead crustal velocity increases more or less uniformly with depth.

The refraction experiment North Atlantic Seismic Project (NASP) [Smith and Bott, 1975; Figure 1] recorded arrivals which, based on time-term analyses, indicated a two-layered crust under the foreland (with arrivals of about 6.1 km s^{-1}, a mid-crustal phase of 6.5 km s^{-1}, and a Moho phase (P_n) of 8.0 km s^{-1}) below the foreland, with a Moho depth there of 26±2 km. Little information on the detailed crustal structure of the orogen is available from this experiment. In contrast, the Hebridean Margin Seismic Experiment (HMSE) [Bott et al., 1979; Figure 1] failed to record any mid-crustal phases on the Hebridean shelf west of the Outer Hebrides. The Moho depth here, based on rather sparse crustal velocity information, was inferred to be 27±2 km. Other experiments east of the Outer Hebrides show that, acoustically, the Moho is a well-defined sharp boundary, which gives rise to good PS reflections [Jacob and Booth, 1977] and continuous high amplitude P-reflections on MOIST [Smythe et al., 1982].

Detailed upper crustal refraction velocity measurements have been determined at sea over several areas of the Hebridean shelf. These velocities suggest that the Lewisian rocks near the surface west of the Outer Hebrides are mainly Laxfordian (Plate 1; Jones [1978, 1981]) and that the sedimentary cover is generally less than 1 km thick. Two-ship expanding spread and constant offset profiles have also been recorded (Plate 1; White et al. [1982]; Hughes et al. [1984]; Jones et al. [1984]). These results may be compared with refraction velocities obtained from the LUST experiment on the mainland of NW Scotland (Figure 1; Hall [1978]), which showed that compressional velocities increase rapidly with depth from less than 5 km s^{-1} near the surface to about 6.0 km s^{-1} at 1 km depth, in an area where granulite facies rocks appear to be absent.

Commercial speculative survey profiles, generally of pre-1973 vintage, are abundant in the foreland area (Plate 1). These data provide three-dimensional control on some basement reflectors, but in general are of limited value, because they are only recorded to 5 or 6 s (15-18 km depth) and, as discussed below, the upper crust down to these depths is generally rather transparent. The lower crust, by contrast, is highly reflective. Two of these speculative lines, GSI lines 0-1 and H [Blundell, 1981] have been reprocessed and are discussed below in relation to WINCH.

Finally, a conductivity traverse which runs subparallel to LISPB (Figure 1; Hutton et al. [1980]) also provides information on Caledonian crustal structure which can be correlated with information on MOIST and WINCH. The northwestern end of the traverse lies on Lewisian basement, and the foreland crust can be modelled as a single block, the base of which lies close to the seismically defined Moho, and which is of a uniformly low conductivity (10^{-5} S m^{-1}; Hutton et al. [1980]). In contrast, the orogen is characterized by a more highly conducting crust, although the boundary between these two regions is poorly defined, due to low data density.

CRUSTAL STRUCTURE ALONG WINCH

We now discuss the main aspects of the crustal structure of the Caledonian foreland. In this context the foreland is considered to extend as far to the SE as the Loch Skerrols Thrust (Figure 1), which we consider to be the southwesterly extension of the Moine Thrust [Bailey, 1917]. The Loch Skerrols Thrust appears to mark a major subvertical offset of Lewisian base-

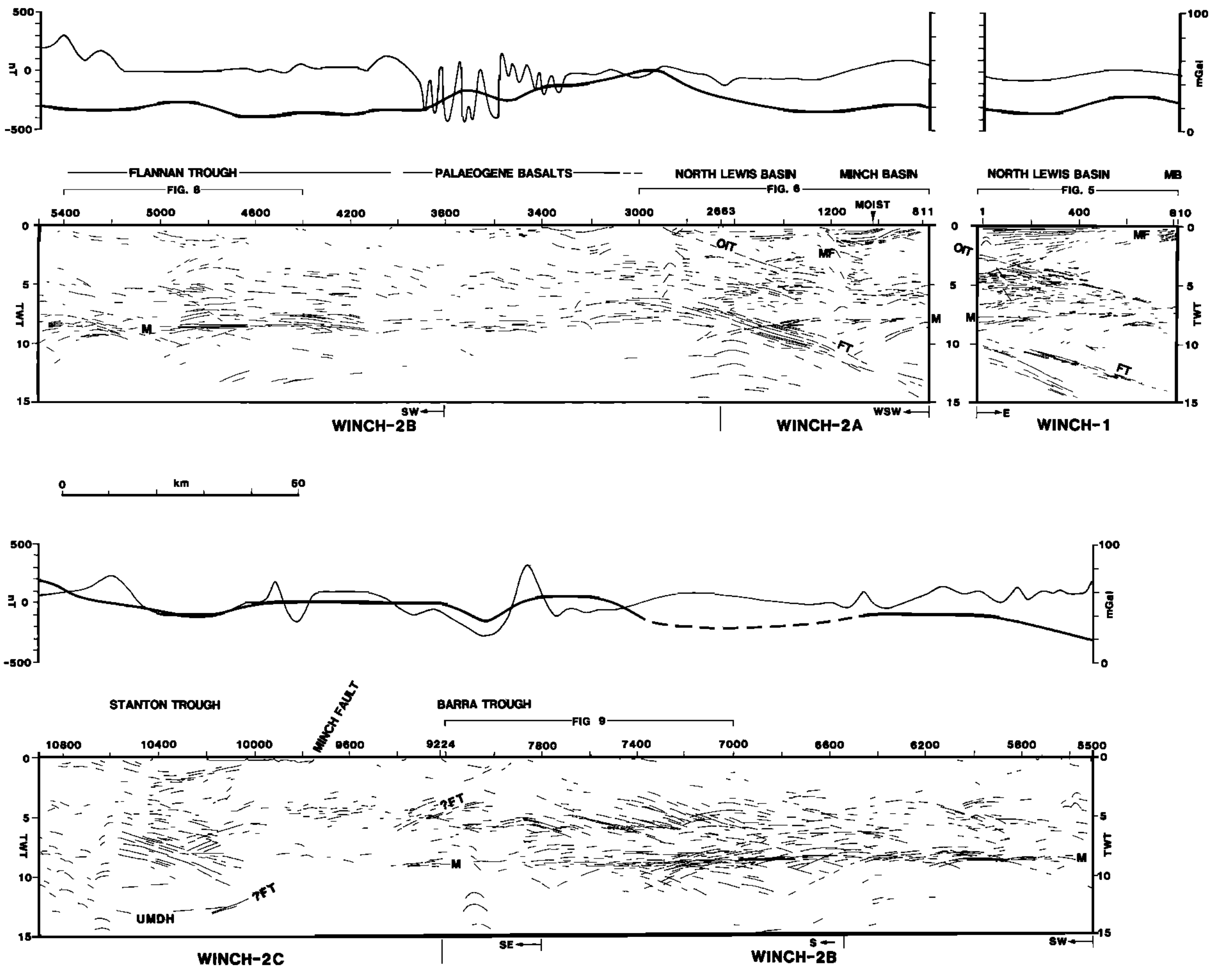

Fig. 2. Unmigrated time line drawing of WINCH-1 through WINCH-2C, with Bouguer anomaly profile (bold line) and aeromagnetic anomaly profile (fine line) drawn above. OIT, Outer Isles Thrust; FT, Flannan Thrust; MB, Minch Basin; MF, Minch Fault; M, Moho; UMDF, Upper mantle décollement horizon, the possible subhorizontal extension of the Flannan Thrust south of the Hebrides. To convert two-way time in seconds to approximate depth in kilometers, multiply by 3.

ment [Westbrook and Borradaile, 1978], and therefore may also mark the orogenic front to the Caledonian orogen. In this paper, however, we shall discuss the part of the foreland to the north of the Camasunary-Skerryvore fault (Figure 1, Plate 2). The region south of this fault, together with Caledonian structures as far south as the Irish Sea, is described by Hall et al. [1984].

Thrusts and Basins

The only basin west of the Outer Hebrides traversed by WINCH is the Flannan Trough (or Outer Hebrides Trough) postulated by McQuillin and Binns [1973] on the basis of gravity data, and established by Jones [1978, 1981] as a downfaulted region with up to 1200 m of Mesozoic sediments. It is poorly imaged (Figure 2, SP 3800-5400). It lacks distinctive reflecting horizons, and, in any case, is far too shallow to be easily studied, because the recording and processing of WINCH were designed to enhance deep crustal reflections. However, despite this, it does appear that the NE part of the Mesozoic trough extends below a cover of previously recognized Palaeogene basalts [Bullerwell,

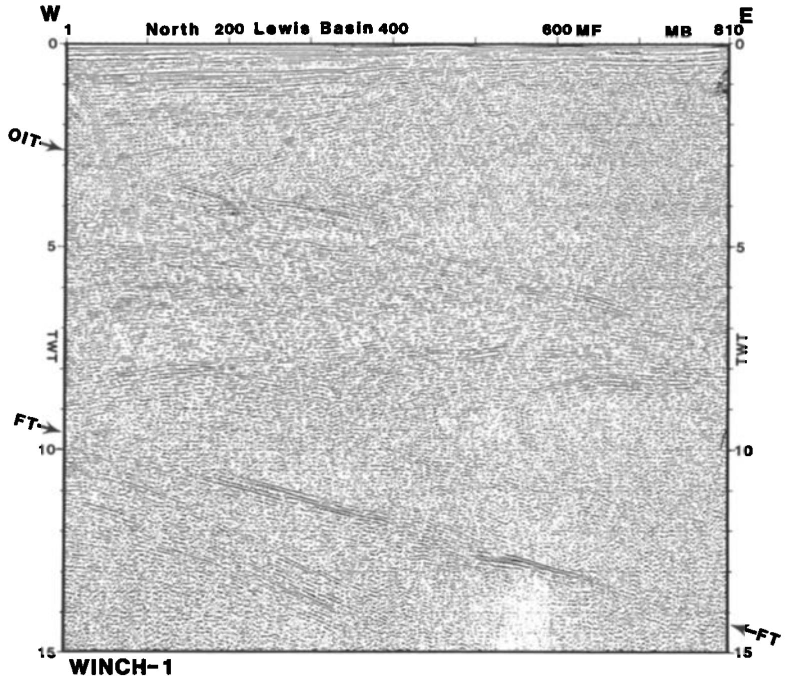

Fig. 3. WINCH-1 30-fold stacked section with low-frequency (7.5-20 Hz) band-pass filter. 100 SP = 5 km. Processing through stack by GECO for BIRPS, 1982; poststack processing and display by GSI for BGS, 1984. OIT, Outer Isles Thrust; FT, Flannan Thrust; MF, Minch Fault; MB, Minch Basin. To convert two-way time in seconds to approximate depth in kilometers, multiply by 3. Note that the Minch Basin has almost died out this far north, and that upper crustal extension is taken up in the North Lewis Basin, which directly overlies the Outer Isles Thrust.

1972], which in turn underlie ?Oligocene-age sediments (Plate 2, Figure 2). The eastern margin of the Flannan Trough, postulated by Jones [1978] to be a major Precambrian shear zone reactivated during the Mesozoic, does not appear to be a feature of any crustal significance, in that no reflections from it are seen, nor are lower crustal layers offset across it.

The major basins crossed by WINCH are the Minch Basin [Chesher et al., 1983], and its north-westerly continuation, the North Lewis Basin (Figure 2). Both these basins are half-grabens. It is significant that, unlike the Flannan Trough, these basins are associated with crustally penetrating reflecting horizons marking the trace of the Outer Isles Thrust at depth (Figures 3-5; see discussion below). Figure 3 shows the Outer Isles Thrust on WINCH-1 well imaged from 3.7 s at SP 1 to about 6.5 s around SP 700. It underlies the westerly dipping reflectors of the North Lewis Basin. The Minch extensional fault, which has more or less died out this far north, can only just be defined as a diffuse zone of faulted basement near the surface, between SPs 600 and 700.

On WINCH-2A/2B, the Outer Isles Thrust is also well imaged, cropping out on the sea bed at SP 2890 (Figure 4). It dips eastward into the lower crust to about 4 s at SP 1300, where it becomes acoustically indistinguishable in the layered lower crust. The Minch Basin is well imaged between SPs 811 and 1150, the strong reflector at around 1.5 s marking the ?Base Jurassic [Chesher et al., 1983]. The Minch Fault zone dips east from outcrop at SPs 1250-1300, to become acoustically indistinguishable in the lower crust at the eastern edge of the section.

South of the Hebrides the Outer Isles Thrust does not give rise to the strong reflections seen north of the Hebrides, and furthermore, the Sea of the Hebrides Basin (the southerly continuation of the Minch Basin; Plate 2), which thins to the SW, has almost died out where it is crossed by WINCH (SP 9800). This observation

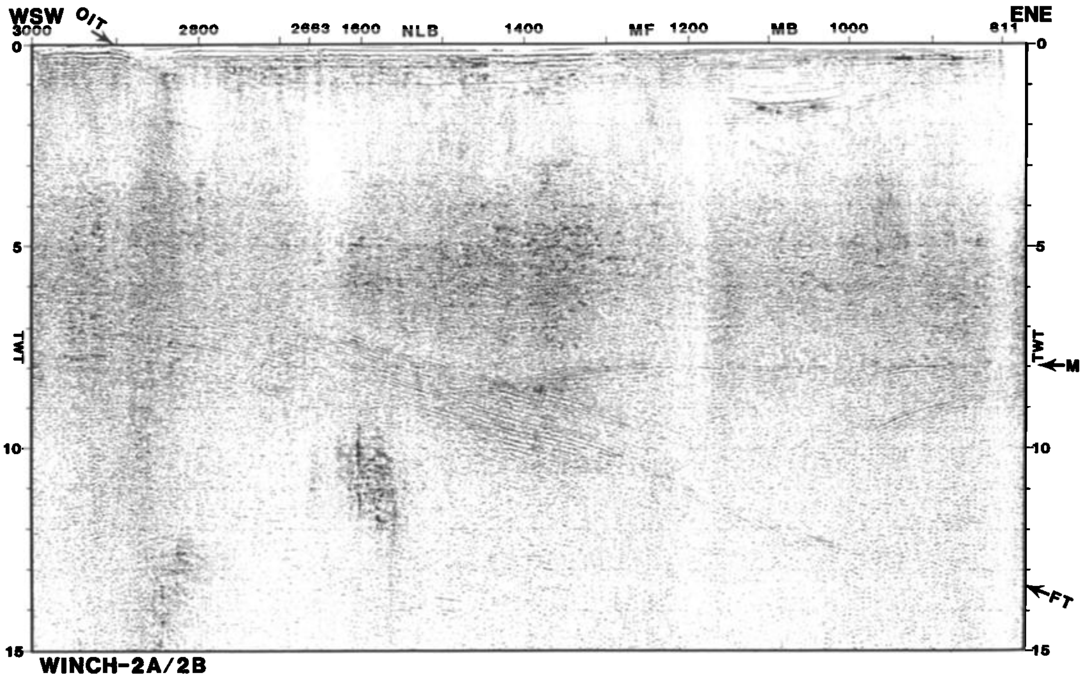

Fig. 4. "Relative amplitude" display of part of WINCH-2A/2B, by GECO, 1982. Bandpass filter is wider (7.5-40 Hz) than in Figures 3, 6 and 7. The east-dipping Outer Isles Thrust crops out at SP 2890. Data in the 1-3.5 s window has a "bleached out" appearance possibly due to unsuitable processing parameters (see text), rather than due to crustal reflection character. High-frequency clusters of hyperbolic reflections around 10 s, SP 1600 and 13 s, SP 2800 are sideswipe, caused by reflectors lying some distance away from the vertical plane of the section. They are omitted from the line drawings such as Figure 2. Abbreviations as for Figure 3. Note that in this region and further south, upper crustal extension is increasingly accommodated in the Minch Basin rather than the North Lewis Basin.

implies either that the presence of the Minch/Sea of the Hebrides Basin is directly related to the lateral extent of the Outer Isles Thrust, or that thrust-zone reflections are only generated where sufficient reactivation by later normal faulting has occurred. We prefer the former interpretation, because basement thrusts can be seen in deep reflection data elsewhere, even when no reactivation has occurred—for example, the Wind River thrust, Wyoming [Brewer et al., 1980].

Thrusts and Basins: Discussion

The fault known on the Outer Hebrides as the Outer Isles Thrust was originally interpreted on MOIST a a sequence of reflectors dipping at about 25° from the seabed north of Lewis into the lower crust [Smythe et al., 1982]. Its reflection character on WINCH is obviously very similar (Figures 3,4). There is little doubt that this sequence of dipping reflectors is indeed the trace at depth of the Outer Isles Thrust, because the reflectors can be traced from WINCH and MOIST onto commercial seismic data, to within 4-5 km of the position of the fault onshore (Figures 5a, b). No other comparable geological feature exists in that area, with which the dipping reflectors could be confused.

However, on the BIRPS data the sense of offset along the fault suggests only extensional movement (the formation of the Minch and North Lewis Basins). There is no direct evidence of thrusting, and Smythe et al. [1982] drew on the evidence of thrusting from onshore studies to suggest that the normal faulting observed offshore must simply be reactivation of an earlier zone of thrusting. Wernicke et al. [1985] and Wernicke [1986] have quest-

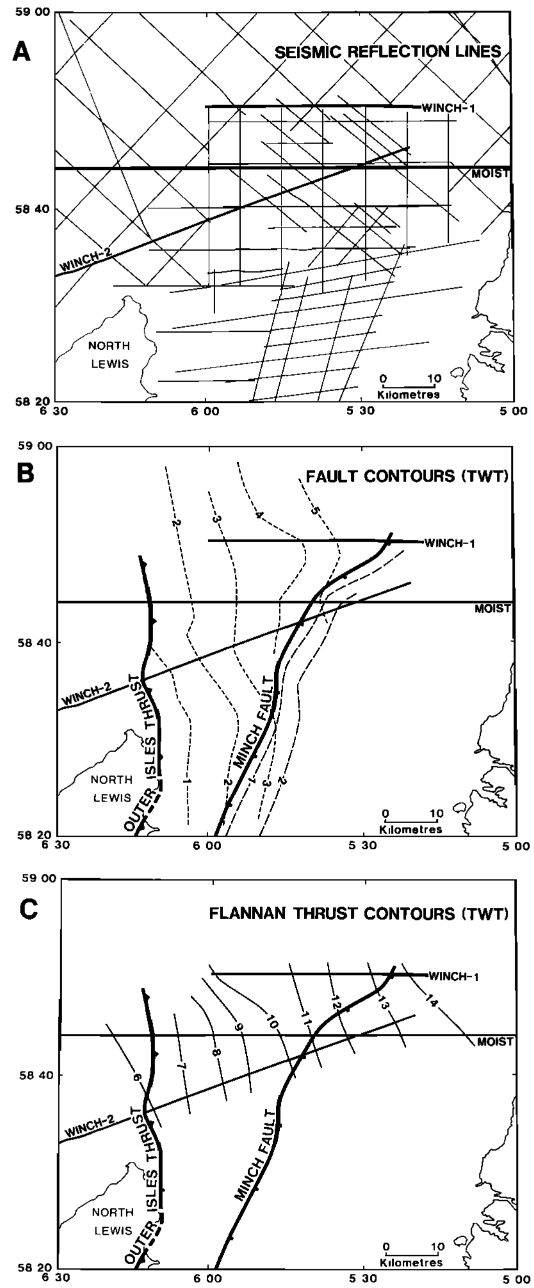

Fig. 5. (a) Location map of North Minch seismic reflection data; MOIST, WINCH-1 and WINCH-2 are 15 s lines; other unlabelled lines are multichannel reflection data shot to 5 or 6 s two-way time (TWT). (b) Unmigrated TWT contours on the Minch Fault (long dashed lines) and Outer Isles Thrust (short dashed lines). Note that the Outer Isles Thrust offshore can be clearly identified with the same feature onshore on North Lewis by mapping it using the commercial data. North of WINCH-2 the thrust is at subcrop below sediments. (c) Unmigrated TWT contours on the Flannan Thrust. At depth it diverges in trend from near-parallelism with the Outer Isles Thrust, and below the Moho its strike is NW-SE.

ioned whether this conclusion is valid, and have proposed that the Outer Isles Thrust may never have actually been a thrust. If this is the case, then the geological evidence onshore must be carefully reexamined and reinterpreted.

The principal evidence onshore that the fault is indeed a thrust includes:

1. A thick (up to 1 km) sequence of mylonites, pseudotachylites and cataclastic rocks [Jehu and Craig, 1925, pp. 621-622], more commonly seen around thrusts than around normal faults.

2. A schistosity developed in the ductile shear zones which intensifies and curves in from the margins to the centre in a thrust sense [Sibson, 1977, p. 195].

3. The presence in the hanging wall of generally higher grade, granulite facies rocks, representing a higher metamorphic grade (and therefore presumably originating from greater depths) than the amphibolite facies rocks which make up the footwall. Unfortunately, no other stratigraphic evidence exists.

4. A shallow (< 25°) dip of the fault zone at the surface.

A period of later extensional movement is indicated by a fairly ubiquitous series of late stage, asymmetric crenulations and chevron folds with consistent down-dip vergence [Sibson, 1977]. The age of the fault rocks is uncertain. They are definitely post-Laxfordian (they cut host rocks of this age), but the only radiometric investigations are whole-rock K/Ar experiments on micaceous mylonites which gave late Caledonian ages (R.H. Sibson in Steel and Wilson [1975].

Although clearly the evidence that the Outer Isles fault is a thrust may be reinterpreted in the light of further studies, we believe that at present the most straightforward interpretation of the data, both onshore and offshore is:

1. Thrusting occurred along the trace of the Outer Isles fault (both onshore and offshore) sometime after Laxfordian times but before the end of Late Caledonian times. However, the close similarity of strike and dip of the Outer Isles fault to the Moine Thrust strongly suggests that

the former is, like the latter, almost completely a late Caledonian feature.

2. Extensional movement occurred later along the trace of the Outer Isles Thrust. The magnitude of the extension and normal faulting varied from being almost insignificant onshore (indicated by the late, asymmetric crenulations and chevron folds) to very major offshore (indicated by the Minch and North Lewis Basins, which lie in the hanging wall of the Outer Isles Thrust). The timing of these extensional movements is almost certainly mainly Mesozoic, since this is the age of the sedimentary rocks deposited in the basins.

In other words, the Mesozoic extensional structures on the Hebridean shelf were most probably strongly controlled in detail by the earlier, Caledonian compressional fabric.

Acoustically transparent upper crust

Apart from the basins discussed in the previous sections, most of the Lewisian basement crossed by WINCH is devoid of significant cover rocks, and the upper part of the crust (to 3-4 s, or 9-12 km depth) is remarkably featureless and transparent, at least on the scale of the wavelengths used in this survey. However, we have to be cautious before making any generalizations about the nature of the upper crust above 3 s based upon multichannel reflection lines like WINCH. Because BIRPS data are collected and processed in order to enhance deep reflections, shallow data (e.g., above 3 s) are sparser than deeper data (for a discussion of seismic data processing see Waters [1981]. The sparsity is determined by the "mute" function, the shape of which is indicated by the roughly triangular area of no-data in the top-right hand corner of Figure 4, before SP 811. Full seismic coverage is achieved only below 3 s, and thus it is conceivable that the transparent upper crust simply is due to the absence of full coverage at shorter travel times.

Another consideration is that in Figure 4, reflectors are displayed according to their relative amplitudes, and at this particular stage there were two data processing problems which tended to enhance the apparent absence of upper crust reflections:

1. An inappropriate spherical divergence correction (i.e., correction for an expanding acoustic wave front), which probably accounts for the "bleached-out" zone between 1 and 3 s, and

2. At 4 s there is a crossover from one deconvolution operator (i.e., correction for signal reverberation) to another, which may exaggerate the apparent contrast between the upper and lower crust seen on WINCH generally.

These problems arise purely in the display stages, and do not stem from the quality of the raw data.

However, other seismic data also show a transparent upper crust. Parts of two GSI speculative survey lines 0-1 and H, shot and processed in 1973, were reprocessed in 1979 by GSI for NERC (Plate 1). The aim of the reprocessing—to see whether the intra-basement reflectors at 4-6 s on the original stacks were real, primary events—was achieved, but despite using all the relevant state of the art techniques available in 1979, the upper crust (0-3 s) still remained largely acoustically transparent. A line drawing of the reprocessed stack of GSI-0-1 has been presented by Blundell [1981, Figure 4).

Notwithstanding the acoustic imaging problems, it is probably a valid generalization (based on observations from all the various processing stages of the reflection data) that the upper crust in the Caledonian foreland is largely transparent to seismic energy in the frequency spectrum 10-50 Hz. There is little indication on WINCH that any of the NW-SE trending shear zones associated with Laxfordian deformation [Watson, 1975, 1977] exist or were acoustically detected, at least in the upper crust. An offshore high-resolution reflection experiment on the crust west of the Hebrides, like the onshore experiment conducted on Lewis by BIRPS in 1983 (R. Jones, personal communication, 1984) would be desirable to test whether the upper crust really is seismically transparent at all wavelengths.

Lower crust

In contrast to the upper crust, the lower crust on WINCH is highly reflective between about 4 and 8-9 s (about 12-30 km depth, Figure 2). Bands of discontinuous (up to 5-10 km long) antiformal reflections (some of which may be off-line), subhorizontal and apparently north-dipping reflections and diffractions make up the lower crustal reflection sequence. Reflector density is somewhat variable. The Moho appears as a discontinuous reflector

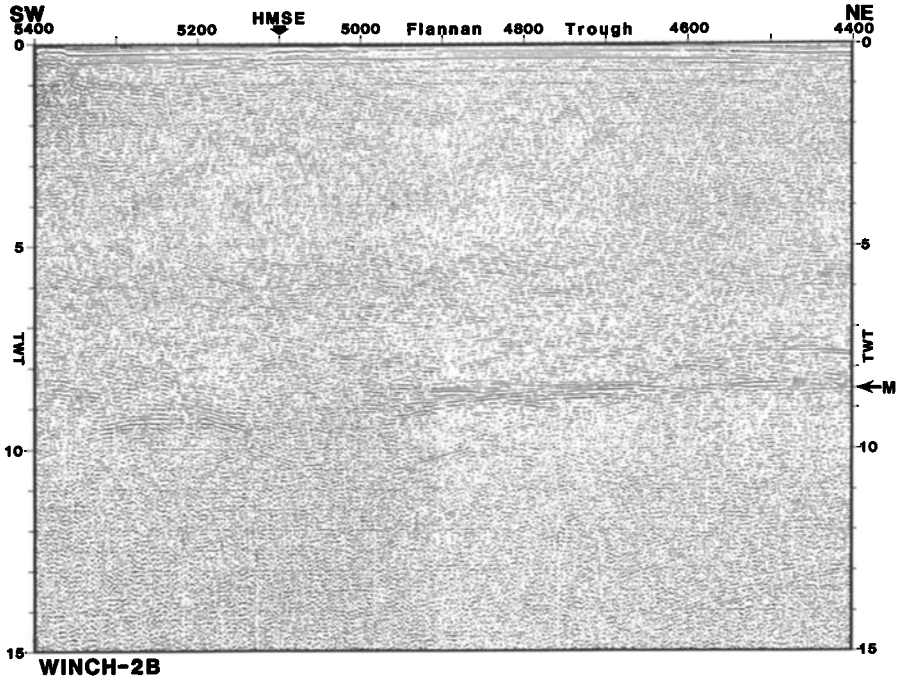

Fig. 6. Part of WINCH-2B (processing as in Figure 5) over foreland NW of Harris (Plate 1). Gently N-dipping reflectors at 0-2 s are from within or just below the Flannan Trough, one of the few areas where upper crustal reflectors occur. The upper crust beneath (2-5 s) shows only incoherent reflections and diffractions, whereas the lower crust (5-8 s) is more reflective. The Moho band of reflections at around 8.4-9 s correlates well with the refraction-defined Moho on HMSE.

or band of reflectors between 8 and 9 s (26-29 km depth) at the base of the lower crustal layer (for example, Figure 6). Variations in amplitude and reflector strength of the Moho sometimes correlate with variations in lower crustal reflectivity, suggesting that here these variations may be due to changes in near-surface conditions (such as presence or lack of sedimentary cover) rather than real variations in lower crustal structure. The bad weather conditions encountered during the part of the survey in the southern Sea of the Hebrides, around SPs 9400-9900 (Figure 2) may also account for the lack in this area of a reflective lower crust or good Moho reflector.

Some of the more distinctive reflecting horizons within the upper part of the lower crustal reflective layer can be traced onto commercial seismic data. For instance, using the commercial data, reflectors with an apparent north dip (Figure 7) can be shown to have a true dip to the east or NE. Also, an antiformal band of reflections at 5.2 s under SP 7900 appears, with the help of the commercial data, to mark a change in regional strike of crustal structure from NNW-SSE, north of SP 7800, to a NNE-SSW trend in the area to the south, below the Barra Trough (Plate 2). The antiform shape itself is, of course, an artifact of the unmigrated seismic data. Its true shape would be revealed by a proper, three-dimensional migration. This change in strike of crustal structure also correlates with a NNE-SSW aeromagnetic trend crossing WINCH at SP 7850 (Plate 3) below the Barra Trough. This trend is presumably Scourian, or Caledonian. The Laxfordian trend (i.e., NNW-SSE) seen in the lower crust north of SP 7800 is the same trend as occurs on the island of South Uist, immediately to the east. A similar trend is also seen in many of the aeromagnetic anomalies over the Hebridean shelf north of approximately latitude 57°N. Although locally (e.g., on the island of Lewis) NW-trending linear magnetic anomalies are caused by Tertiary dykes, these have rather a distinctive character (nearly all

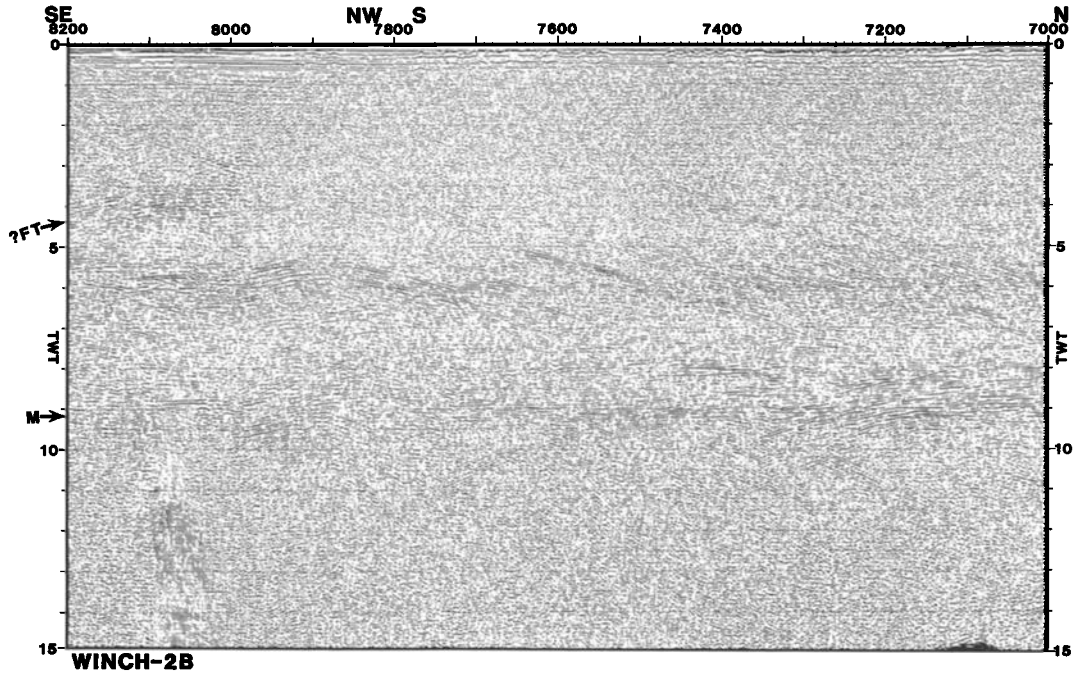

Fig. 7. Part of WINCH-2B (processing as in Figure 3) west of South Uist and Barra (Plate 1). Note the apparent northward-dipping reflections at 4-7 s between SPs 7000-7800; their true dip direction is ENE. The antiform at 5.2 s under SP 7900 marks a change in regional structural trend (see text), which is further complicated by the change in line direction at SP 7800. The band of reflectors at 3.5-4.5 s, below SPs 8000-8200, may be the southerly occurrence of the Flannan Thrust.

negative) and are not observed on the area of WINCH around SP 7800.

The lower crustal reflective layer is ubiquitous on WINCH west and south of the Hebrides, but to the NE it is much less obvious, and may terminate at the Outer Isles Thrust. This termination is seen on WINCH-1 (Figure 3) and MOIST [Smythe et al., 1982; Brewer and Smythe, 1984], although it is not so obvious on WINCH-2A (Figure 4). At present we cannot be sure that this termination is not simply a data-processing effect, but if it exists it implies that the Outer Isles Thrust is a very important tectonic boundary north of the Hebrides. However, no equivalent truncation of the lower crustal reflective layer occurs along the strike of the Outer Isles Thrust south of the Hebrides.

Moho

The acoustic character of the Moho WINCH is more varied and complex than on MOIST. In particular, instead of the rather simple 3-4 cycle reflector band seen on most of MOIST, a 3-8 cycle band of reflections occurs on WINCH, and amplitudes are much more variable. In some places (e.g., Figure 2, SPs 3700-4100) the Moho is effectively marked only by the base of the zone of lower crustal layering. This circumstance cannot be ascribed to changes in the near surface, because the most likely cause—Tertiary basalts at or near outcrop (Plate 2), indicated on Figure 2 by the high frequency, high amplitude magnetics—only partially coincides with the zone of Moho variation.

Changes of Moho character also apparently correlate with the presence or absence of the reflective lower crust. On much of MOIST there is a sharp, high-amplitude Moho, but no strongly reflective lower crust, whereas on WINCH a reflective lower crust occurs with a less well-defined Moho beneath. Jacob and Booth [1977] also inferred a sharp Moho boundary, based on a wide-angle seismic experiment which recorded good PS reflections east of the Outer Isles Thrust. This result therefore is consistent with the Moho seen on MOIST.

TABLE 1. Correlation of Crustal Reflection Character on MOIST and WINCH

	Foreland		Orogen	
Area Data	West of OIT WINCH (+MOIST)	East of OIT MOIST	West Orkneys MOIST	North Sea SALT-2 (W of Central Graben)
Later crustal extension		T	T	
Lower crust acoustically layered	T			T
Lower crust transparent		T	T	
Moho acoustically sharp		T	T	
Moho banded	T			T

T indicates "true" or "present". OIT is Outer Isles Thrust.

Some of the Moho reflection differences between MOIST and WINCH might be explained by different processing parameters, in particular by different poststack predictive deconvolution operators, designed over different time windows of the respective sections. For instance, it was found during the testing stage of MOIST processing, that a poststack deconvolution operator, if designed around the Moho reflector sequence, easily "spiked" the Moho reflection into a single pulse. Such an operator was not chosen, however, because it also introduced excessive noise.

For the present, we assume that the contrast between Moho character of MOIST and WINCH does, therefore, seem to be real. Note, however, that the Moho contrast cannot simply be explained as differences between orogen and foreland. Although much of the well-defined Moho on MOIST lies below the orogen, it also extends below the foreland east of the Outer Isles Thrust. Furthermore, on the portion of the SALT-2 line in the western North Sea, west of the Central Graben (well away from the Caledonian foreland), the lower crustal character is rather like that on WINCH [Barton et al., 1984]. Perhaps the sharpness of the Moho reflection can be correlated with the amount of extension that the crust has undergone. Table 1 summarizes these conclusions.

Rather surprisingly, the travel time of the Moho reflections does not vary significantly with variations in upper crustal velocity structure. The most obvious example of this occurs under the North Lewis Basin, where velocity pull-down would be expected, but is not seen (Figures 2-4). This relationship implies in this area a close connection between travel time to the Moho and depth of the Moho.

Upper Mantle

The final aspect of WINCH which makes it an outstanding example of deep seismic reflection data is the presence of strong mantle reflectors. MOIST, WINCH-1 and WINCH-2A provide excellent three-dimensional control on one of these, the Flannan Thrust (Smythe et al. [1982]; Figures 2-5). We interpret this feature as a thrust because it has a similar reflection character, and a similar geometry and Caledonian trend to the Outer Isles Thrust. However, no definite structural offsets have been identified across it, so this must remain a working hypothesis. The thrust dips easterly at 25°-30° (based on depth migration of line drawings), subparallel to the Outer Isles Thrust, from at least 14 s (about 45 km depth) and passes updip through the Moho. The Moho is not clearly offset, but on MOIST there is evidence that the Moho may change from the 3-4 cycle reflection characteristic of most of the profile to the more complex multicycle reflection character west of the intersection with the Flannan Thrust. The thrust does not cut up to the surface but apparently flattens into the reflective lower crustal layer between SPs 2800 and 3000 at a depth of about 18-20 km (Figures 2, 4). This behavior contrasts with that of the Outer Isles Thrust, which terminates, or flattens, within the reflective lower crust. It thus appears that the reflective lower crust is a zone which cannot support significant differential stresses.

How far does the Flannan Thrust extend to the south-west? A rather poorly defined reflector occurs in the expected along-strike position of the Flannan Thrust under the southern Sea of the Hebrides (Figure 2, SPs 10,000-10,400). It is possible that the rather weak character of this reflection is due to the bad weather which was encountered here during shooting, resulting in poor and noisy data quality. It may also be significant that this is the same area where the Outer Isles Thrust and the Sea of the Hebrides Basin also fade out southwards. This possible southern extension of the Flannan Thrust lies at a higher crustal level than to the north. Updip the reflection flattens out at about 5-6 s (15-18 km depth) between SPs 8000 and 8200, i.e., near the top of the lower crustal reflective layer (Figure 7). Downdip it appears to pass into a subhorizontal reflector 12-13 s (35-40 km) deep (SP 10,100, Figure 2). This mantle reflector extends about 150 km farther SE under the Stanton Trough before disappearing just to the north of the surface trace of the Highland Boundary fault (see Hall et al. [1984]; Hall [1985] and Hall [1986] for further discussion). The subhorizontal reflector clearly lies in the mantle, and its relationship to the Flannan Thrust implies that it might be a décollement surface from which the thrust cuts up through the crust. Without more information this remains speculation, but to our knowledge this is the most continuous mantle reflector yet recorded on deep reflection data. This reflector shows clearly that acoustic boundaries do exist below the Moho, and they should be looked for in future deep seismic studies [McGeary and Warner, 1985].

IMPLICATIONS OF THE CRUSTAL REFLECTION CHARACTER

It is tempting to correlate the variation in reflection character of the ancient Hebridean craton with current patterns of deformation in continental crust deduced from study of earthquakes. Studies of fault zones in continental crust suggest that the maximum depth of seismic activity, which is apparently related to background heatflow at the earth's surface, can be modelled as the transition from an upper crust deforming under a pressure-sensitive frictional regime to a lower crust deforming under strongly temperature-dependent quasi-plastic mylonitization [Sibson, 1982]. This idea has been supported and expanded upon by Chen and Molnar [1983] from studies of crustal and upper mantle earthquakes. Within cratons (where the age of the last tectonic event is greater than 250 Ma) seismicity occurs only in the crust, down to a maximum depth, depending upon the heat flow, of 25±5 km. However, in regions of recent continental convergence Chen and Molnar found that the uppermost mantle can also be seismically active even though the overlying lower crust is aseismic. This relationship can be explained if it is assumed that deformation in the crust is dominated by quartz-rich rheologies, and in the mantle by olivine-rich rheologies. At upper mantle temperatures olivine-rich rocks remain brittle, and deform seismically [Chen and Molnar, 1983], but the overlying lower crust is weak and ductile. Thus the lower crust is a region where concentrations of strain might occur, and where detachment of upper crustal crystalline nappes can take place.

The changes in reflection character on WINCH can be related to this model of crustal and upper mantle deformation [Matthews and Hirn, 1984]. North of the Hebrides, the Outer Isles Thrust and the Flannan Thrust both pass into, but not through, the internally reflective lower crust. This implies that the lower crust is a zone of concentrated strain that accommodated movement along these fractures when they were active. Furthermore, if the identification of the Flannan Thrust south of the Hebrides and its associated subhorizontal mantle décollement is correct, then its geometry suggests that the upper mantle seismic zone of elastic deformation lay between this décollement horizon and the Moho, i.e., between about 27 and 40 km depth (for example, 9-13 s, SP 10,400 of Figure 2). The upper mantle ductile zone below this elastically deforming region is acoustically unresponsive, and thus does not appear to have the same pronounced reflection character as the lower crustal ductile zone.

The correlation between our results on

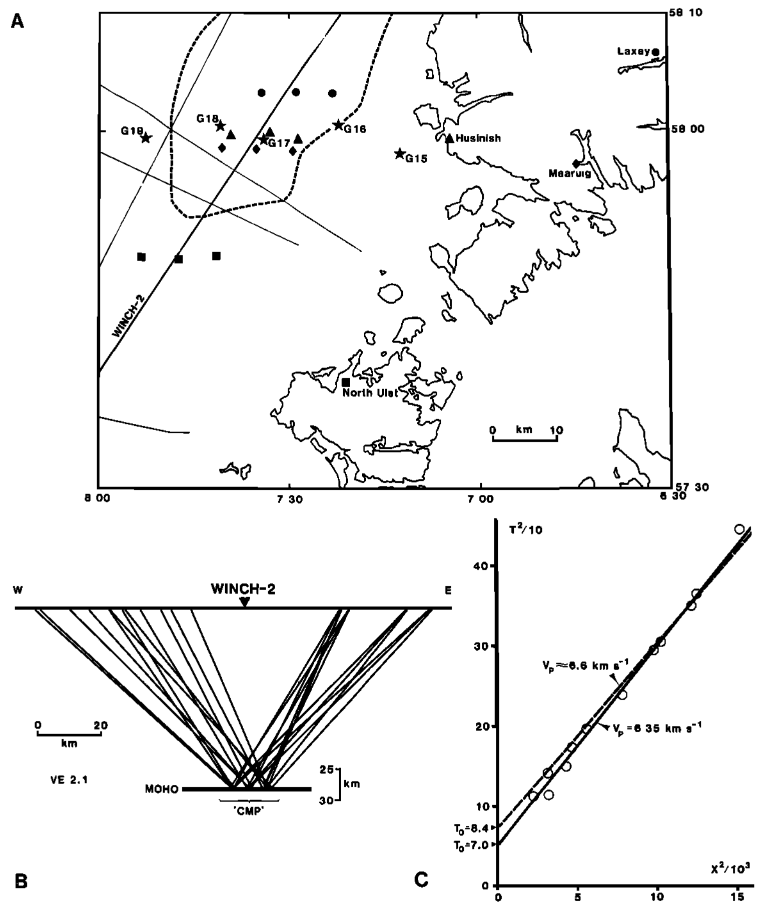

Fig. 8. (a) Detail of HMSE and WINCH locations. Stars represent five of the HMSE explosion shot points (G15-19) along the 58°N parallel. Other shot points lie further east or west. Four recording stations on the Outer Hebrides are shown. They recorded all shots; for each receiving station the three shot-receiver mid-points nearest to WINCH are marked by the symbol corresponding to the station. Moho wide-angle reflections were observed at these 12 mid-points closest to WINCH. Thin lines are other commercial multichannel reflection profiles recorded to 6 s TWT. Dashed line outlines the Flannan Trough. HMSE data from Armour [1977], summarized by Bott et al. [1979]. (b) Projection of wide-angle Moho reflection rays onto an E-W plane at 58°N, along a NNE-SSW direction parallel to WINCH, to simulate a common mid-point (CMP) gather. (c) T^2-X^2 graph showing least squares fit (solid line) to 12 wide angle reflection times corresponding to the mid-points shown in Figures 8a and 8b. Dashed line shows the poor fit when the line is constrained to pass through T_0 = 8.4 s, corresponding to the vertical two-way travel time to the Moho as seen on WINCH-2. This discrepancy suggests a strong velocity gradient in the lower crust (see text).

WINCH and those from current earthquake studies depends very strongly on the assumption that the Moho identified geophysically today is geologically the same Moho that existed or was formed during the movements of the thrusts in the early Palaeozoic. However any correlation between Moho character and amount of post-Caledonian crustal extension (Table 1) would suggest, by contrast, that the present-day Moho may in fact be a considerably altered remnant of the Caledonian Moho.

The reflection character of the Cale-

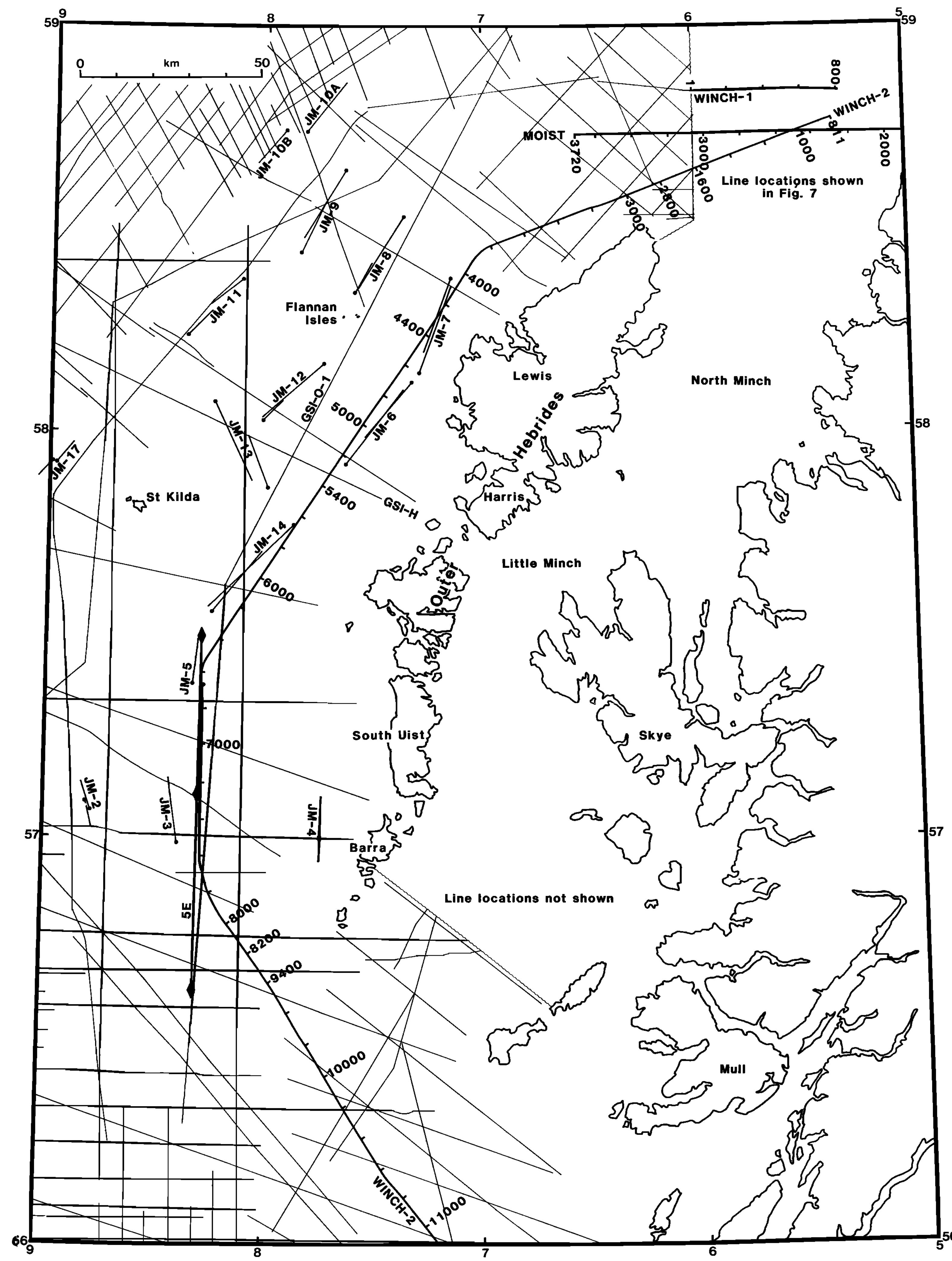

Plate 1. Seismic reflection and sonobuoy refraction data west of the Hebrides. Bold lines MOIST and WINCH are annotated with shot points. Short line segments labelled JM are sonobuoy refraction stations [Jones, 1978, 1981]. Line 5E (diamonds at mid-point and ends) is a two-ship expanding spread profile [White et al., 1982, Jones et al., 1984]. Thin lines denote other (mostly industry) reflection data shot 1970-1983.

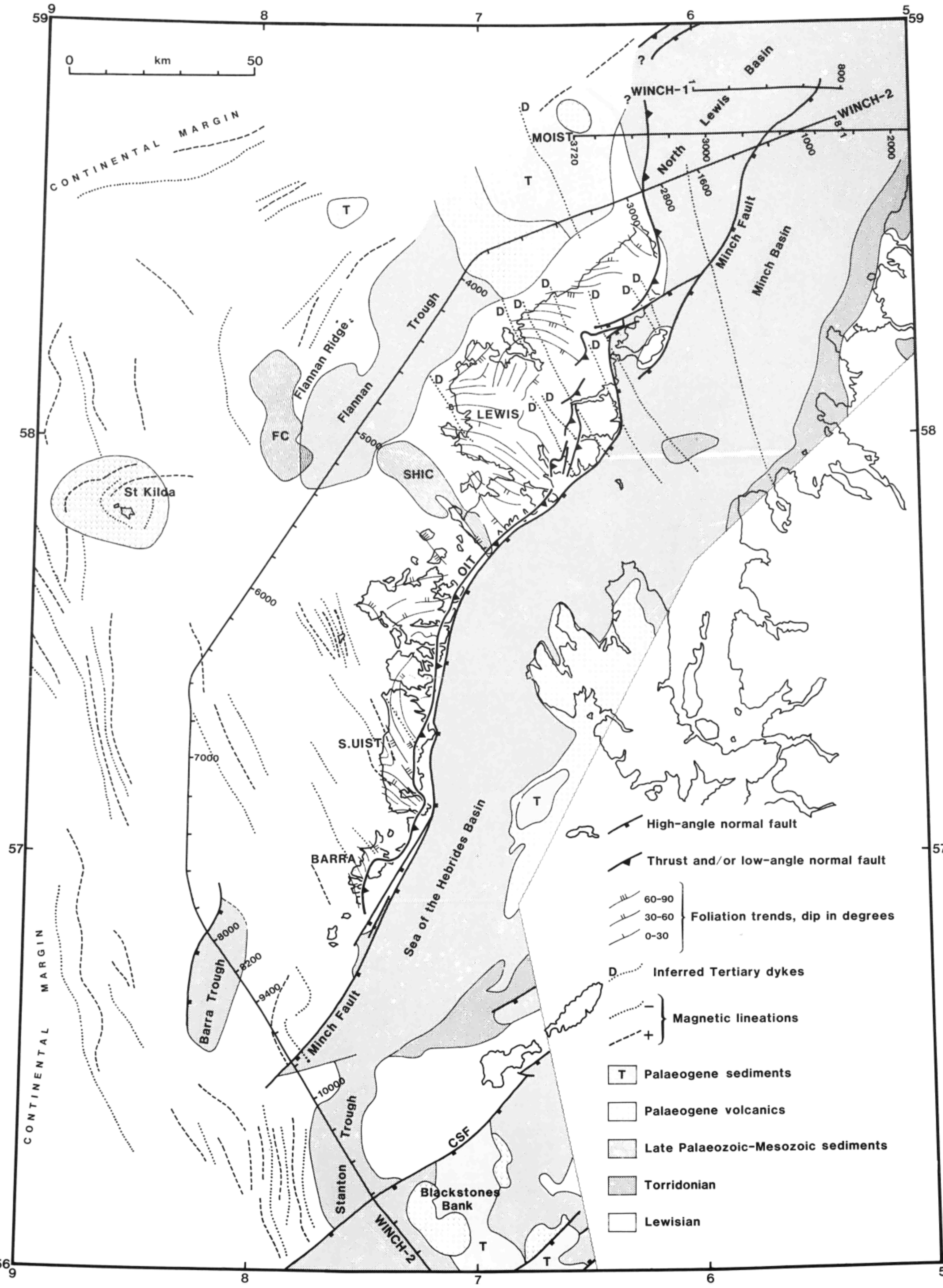

Plate 2. Geology of the foreland relevant to the interpretation of MOIST and WINCH. Foliation trends on the Outer Hebrides are taken from unpublished BGS tectonic maps. SHIC, South Harris igneous complex; FC, "Flannan complex" of high-amplitude magnetic anomalies; OIT, Outer Isles Thrust; CSF, Camasunary-Skerryvore Fault. Note how the throw of the Minch Fault decreases to zero north and south of the Outer Hebrides (see text).

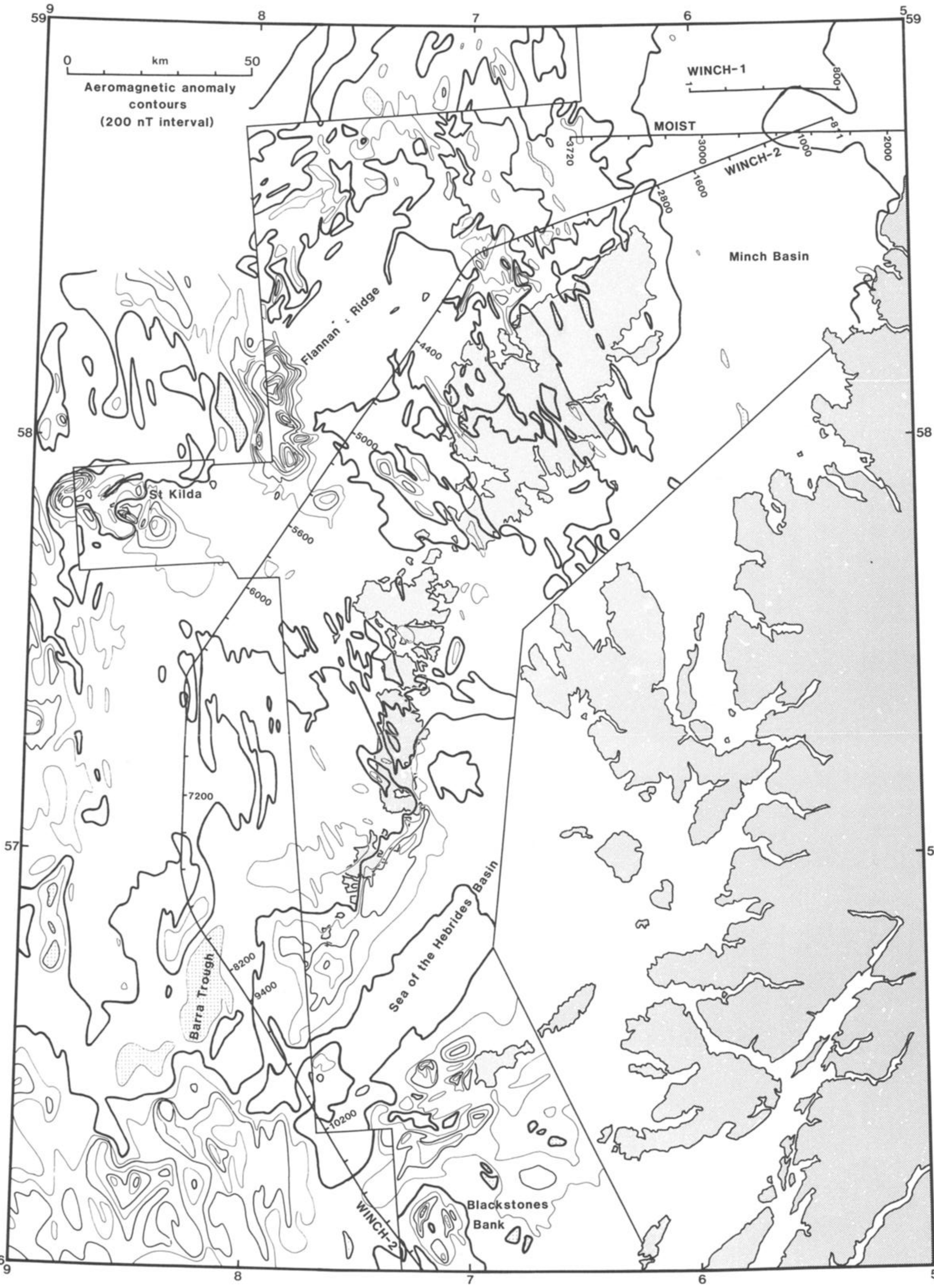

Plate 3. Aeromagnetic anomaly contours at 200 nT interval, IGRF removed. Bold line = 0 nT, negative closures stippled. Fine contour lines at +200, 600 nT, etc., semibold lines at +400, 800 nT, etc. Data in central polygon from BGS surveys, E-W flight line spacing 2 km, data to W from commercial survey held by BGS, E-W line spacing 8 km. Contours over very steep-gradient anomalies around St Kilda and the "Flannan complex" at 58°N, 8°W have been simplified, and some omitted.

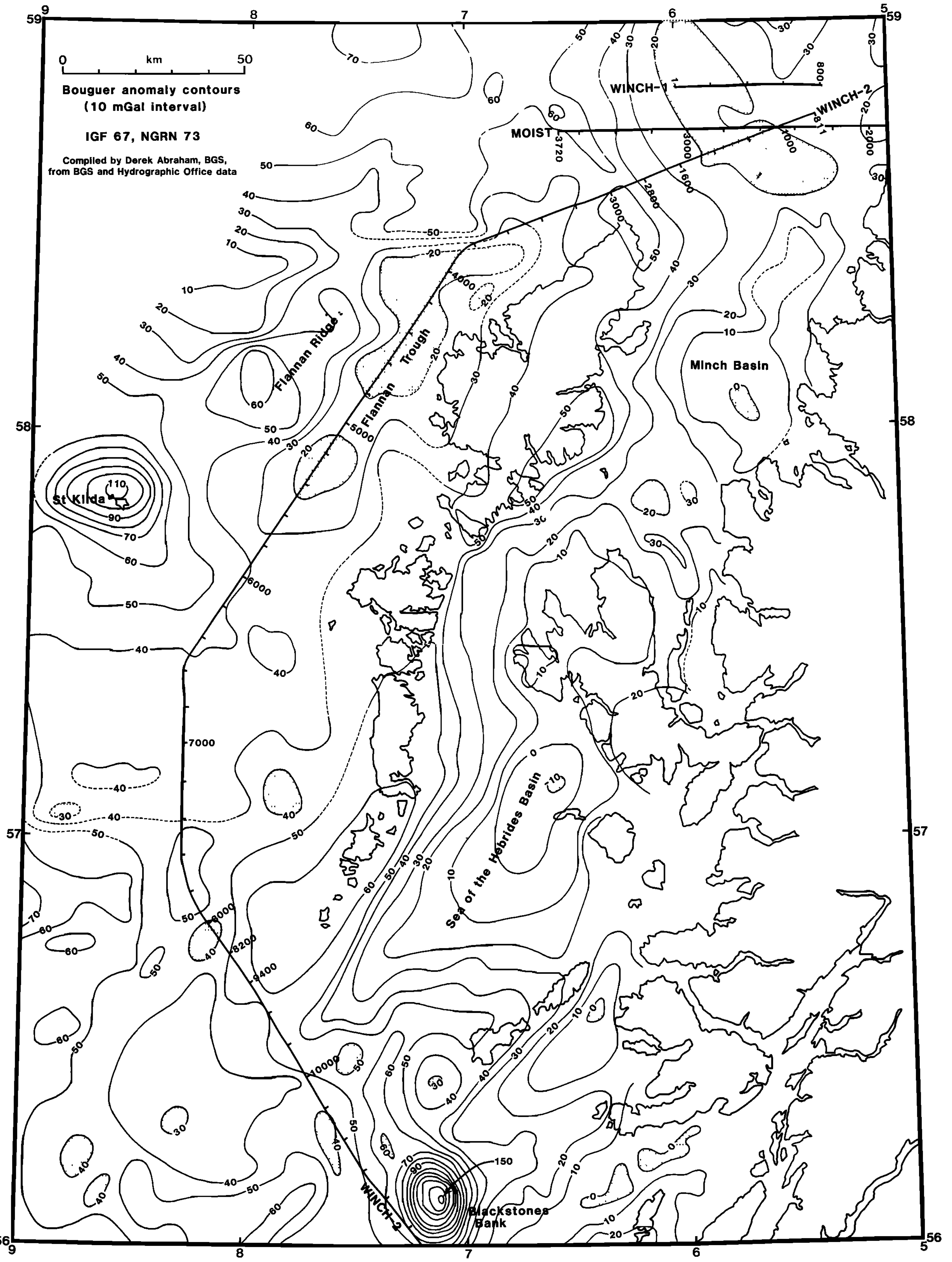

Plate 4. Bouguer anomaly contours at 10 mGal interval compiled and reduced by D. Abraham, BGS, from BGS and Admiralty Hydrographic Office surveys. Areas of poor quality or nonexistent data shown by dashed contours. Note the regional high over the eastern flank of the Outer Hebrides.

donian foreland on WINCH is quite different from the character of the foreland to the Appalachian and Ouachita mountain belts, where they have been crossed by COCORP profiles. Three COCORP lines can be compared with WINCH: the Northern Appalachian survey [Ando et al., 1983], the Southern Appalachian survey [Cook et al., 1979, 1981] and the Ouachita survey [Nelson et al., 1982]. The foreland basement in all areas is of Grenville age, and is essentially devoid of internal reflecting horizons. Assuming that this circumstance is not due to the different surveying techniques, or due to complete absorption of seismic energy in the sedimentary cover (which seems unlikely, since cover types and thicknesses vary considerably between the COCORP profiles), then the Grenville lower crust is acoustically completely different from the Lewisian lower crust. In most areas no clear Moho reflection occurs at the base of Grenville crust. If a seismically transparent crust is indeed characteristic of the Grenville province then the position of the Grenville front under Scotland might be detectable on this basis. Further deep profiles are clearly required to establish the reality and extent of the apparently transparent lower crust recorded on the eastern end of MOIST.

REASSESSMENT OF THE EARLIER GEOPHYSICAL STUDIES

Hebridean Margin Seismic Experiment

This refraction experiment can be reanalyzed using the WINCH data. Travel paths of the main shot line of HMSE cross WINCH on the Hebridean shelf in the region of 58°N (Figures 1, 8). Time-term analysis of the refraction data was used [Bott et al., 1979]; the time-term associated with a particular shot or receiver station is the delay caused to the refracted headwave by the travel up from (or down to) the refractor through the higher layers, relative to the time it would have taken the headwave to get to the station, if the station had been situated on the refractor itself. Time-term plots show up the variation of structure along a line, and the time-terms can be converted to depths using simple formulae. The principal crustal results from time-term analysis of HMSE are (1) ground wave (P_g) phase of V_p=6.2 km s^{-1}; (2) mean crustal velocity of 6.4±0.2 km s^{-1}, with a corresponding crustal thickness of 27±2 km; (3) no evidence for a mid-crustal higher velocity layer such as that observed NW of the Scottish mainland [Smith and Bott, 1975]. In addition, analysis of strong, wide-angle reflections from the Moho (P_mP) received on Lewis from shots offshore yielded a rather poorly-determined mean crustal velocity of 6.2±0.2 km s^{-1}. A fuller presentation of these data is found in Armour [1977].

Only one shot, G17, lies near the part of WINCH adjacent to the HMSE line. It lies 1 km SE of SP 5060 (Figure 8a), where the Moho reflection is at 8.4 s (Figure 6). The time-term for G17, using an assumed crustal velocity of 6.6 km s^{-1}, a mantle velocity of 8.0 km s^{-1}, and correcting for the sedimentary cover of the Flannan Trough, is 2.49 s [Armour, 1977, Table 4.5]. As this value is relatively insensitive to the assumed crustal velocity used in its calculation, we can combine it with the vertical travel time T_o of 8.4 s, taken from WINCH, to reestimate the mean crustal velocity. A graphical method shows this to be 6.4-6.5 km s^{-1}, in good agreement with Bott et al.'s conclusions quoted above.

Can the wide-angle reflection data also be related to WINCH? We have considered only those reflection depth points located near to WINCH (Figure 8) to calculate the mean crustal velocity. Since the Moho along WINCH from SP 4900 to SP 5520 is flat (albeit with an apparent "hole" between SPs 5000-5200), we note that by projecting the raypaths in a NE-SW direction (i.e., parallel to WINCH) onto an E-W plane at 58°N gives us a rough "common mid-point" gather (Figure 8b). The 12 mid-points which are all within 6 km distance of WINCH yield

$$V_p = 6.35 \pm 0.01 \text{ km s}^{-1}$$
$$T_o = 7.0 \pm 0.4 \text{ s}$$
$$Z = 22.2 \pm 1.3 \text{ km}$$

(Offsets 47-124 km). These are shown on the T^2-X^2 plot of Figure 8c. A fit using the 7 internally most consistent points—rejecting the four lowest-offset points and the one furthest-offset point—yields

$$V_p = 6.47 \pm 0.01 \text{ km s}^{-1}$$
$$T_o = 7.8 \pm 0.5 \text{ s}$$
$$Z = 25.1 \pm 1.7 \text{ km}$$

(Offsets 68-112 km).

Whereas the velocity is well determined in these calculations, the intercept T_o is around 1 s smaller than that seen on

WINCH. However, it is poorly determined, due to the lack of points at short ranges. Various calculations on subsets of the data give similar results. Conversely, a (visual) fit on a T^2-X^2 plot, constrained to go through T_0=8.4 s (i.e., corresponding to WINCH), gives a crustal velocity of around 6.6 km s^{-1}, but the line thus fitted (Figure 8c) is clearly skewed to the trend of the data.

There are no obvious discrete normal-incidence reflections in the range 7-8 s on WINCH to account for these intercept times derived from HMSE. The mismatch may, however, be explained by assuming that there is a fairly strong velocity gradient, or a number of discrete velocity discontinuities, in the lower crust, within the zone of the lower crustal acoustic layering on WINCH. This layering would therefore appear to yield wide-angle, but no vertical incidence, reflections. In summary:

1. A mean crustal velocity of 6.4±0.1 0.1 km s^{-1} is consistent both with Bott et al.'s original estimate and with the reflection data.
2. The crustal thickness, assuming this velocity and applying it to WINCH, is around 27.0±0.5 km.
3. There is probably a strong velocity gradient within the layered lower crust, but there are no major first-order velocity discontinuities.

Amplitude modelling of both the normal-incidence and wide-angle reflections would be desirable to test these conclusions.

LISPB and Conductivity

The crustal character shown by the WINCH data cannot be directly compared with crustal models obtained from the LISPB refraction experiment [Bamford et al., 1978] nor with Hutton et al.'s [1980] north Scotland conductivity model, since both of these sets of data lie to the east, almost completely within the orogen, across the regional Caledonian strike (Figure 1). Hutton et al.'s conductivity model and Cassell's [1982] refinements to Bamford et al.'s LISPB model suggest an absence of horizontal layering within foreland Lewisian crust. This is, perhaps, consistent with the reflection-free character of the upper crust and lower crust (east of the Outer Isles Thrust) revealed on MOIST, which also suggests an absence of significant horizontal layering [cf. Brewer and Smythe, 1984].

Two-Ship Multichannel Experiments

Several two-ship expanding spread and constant-offset profiles were recorded west of the Hebrides in 1981 [White et al., 1982]. The N-S segment of WINCH-2, SPs 6600-7600, is located along expanding spread profile 5E (Plate 1), which has its mid-point at about SP 7260 on WINCH-2. A least squares fit to first arrivals in the range 8-67 km yielded a P_g of 6.28±0.01 km s^{-1}, but no higher velocities were observed [Jones et al., 1984]. Amplitude modelling of line 5E suggests that the crustal velocity increases very slightly with depth, from about 6.3 km s^{-1} at 2 km depth, to 6.4 km s^{-1} at about 4 km and deeper [Hughes et al., 1984]. These figures are in good agreement with the HMSE results discussed above.

It is not clear precisely what these velocities signify in terms of rock type, nor can they be interpreted in conjunction with the reflections seen on WINCH, since they were recorded in an area where the upper crust is transparent. The expanding spread and refraction data do not reveal any sign of the reflective lower crust seen on WINCH.

FORMATION OF THE OUTER HEBRIDES BLOCK

The Outer Hebrides appears to have been a positive block throughout much of its history, since after Laxfordian times it was apparently never covered by a thick sedimentary sequence. This fact has previously been attributed to buoyancy caused by an unusually granitic (and therefore low density) basement which is observed onshore [Watson, 1977] and inferred from low refraction velocities recorded offshore [Jones, 1981]. However, the WINCH data, and earlier studies, also show the following:

1. The throw on the Minch Fault decreases abruptly north and south of the geographical limits of the Outer Hebrides (Plate 1, Figure 5).
2. The deepest part of the Minch Basin lies generally east of the central Outer Hebrides, where the topography is highest (Smythe et al. [1972] and Figure 9).

These correlations suggest an alternative explanation for the presence of the Outer Hebridean block: that it comprises the isostatically uplifted footwall to the Minch normal fault system. The hanging wall of this system is delineated by the Minch Basin and Sea of Hebrides Basin.

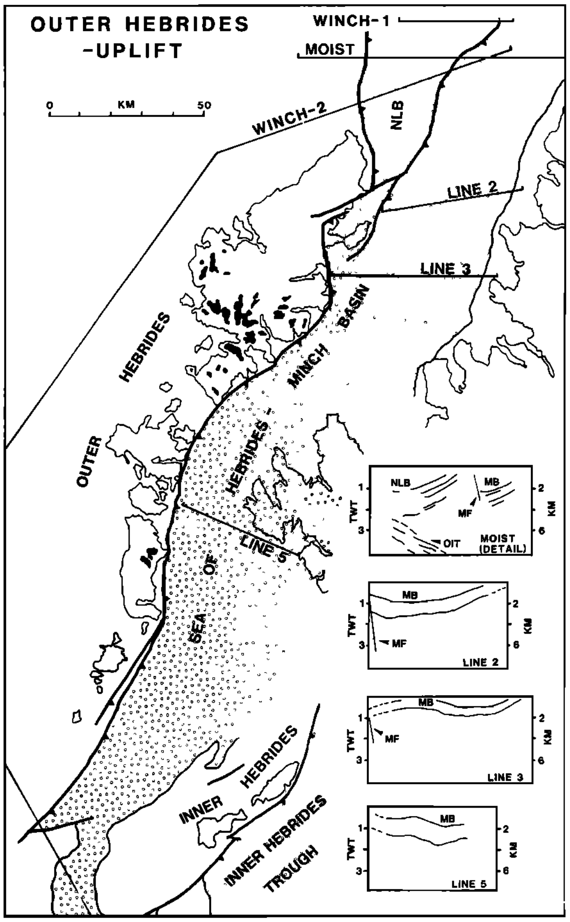

Fig. 9. Simplified geological map (see Plate 2) showing the approximate correlation between the geographical extent of the Outer Hebrides and the Sea of the Hebrides-Minch Basin. Land above 330 m on the Outer Hebrides is shaded black. Line drawing sketches of seismic reflection sections (MOIST, Smythe et al. [1982]; lines 2, 3 and 5, Chesher et al. [1983]; see Figure 2 for line drawings of the WINCH profiles) are crudely depth-converted to show that the Permian-Mesozoic basin infill is generally of the order of 3 km. The uplift of the Outer Hebrides block is very approximately 10% of the basin depth, suggesting (see text) that the uplift of the Outer Hebridean block has occurred as an isostatic response to basin formation [cf. Jackson and McKenzie, 1983]. The same mechanism may apply also to the Inner Hebrides.

The ages of the basin infill suggest that fault movements (and hence uplift of the Outer Hebrides) occurred mainly during the Late Palaeozoic and the Mesozoic.

Jackson and McKenzie [1983] have examined general constraints on the geometrical evolution of normal fault systems. They find that, to a first approximation, the amount of uplift of the footwall expected along a normal fault is approximately 10% of the throw on the fault. The great majority of the Outer Hebridean archipelago is less than 300 m above sea level, although in a few spots heights range up to 800 m (Figure 9). Direct comparison with the depth of the Minch Basin is difficult because, unfortunately, the sedimentary thicknesses and total vertical displacement within the Minch basin are poorly known. Smythe et al. [1972] inferred from early and unsophisticated seismic reflection data recorded onshore on Skye that the Permian-Mesozoic infill in the deep part of the basin exposed there is up to 2.2 km thick. They also estimated from gravity modelling that there is an additional 1.5-2 km of Torridonian preserved below. Reinterpretation of the reflection data mainly requires the replacement of the interval velocity of 3.0 km s^{-1} used in 1972 for the Permian and Mesozoic rocks with a higher figure of 4.0 km s^{-1} derived from the more modern and more widely spread reflection data. This gives a greater average thickness of around 3 km in the center of the basin. Offshore, only a few, poor quality reflection lines exist (e.g. Chesher et al. [1983]; see Figure 9). These, too, suggest that the sedimentary section in the Minch Basin is 3-4 km thick. According to the "10%" criterion of Jackson and McKenzie, this amount of infill would have been quite sufficient to explain the present elevation of the Outer Hebrides as an isostatic response to normal faulting on the Minch Fault.

Hipkin and Hussain [1983, Figures 11, 12) have used the data of Smythe et al. [1972] and Chesher et al. [1983] to produce a stripped gravity map of Scotland. Plate 4 shows a new compilation of additional gravity data, extending the coverage over the shelf west of the Hebrides which was omitted from Hipkin and Hussain's data set. It confirms the reality of the regional gravity high over the eastern flank of the Outer Hebrides just west of the Minch Fault system [McQuillin and Watson, 1973].

CONCLUSIONS

The WINCH profile across the Caledonian foreland shows the following:

1. The upper crust is largely acoustically transparent, and little evidence of the trace of Precambrian structures is seen.

2. In contrast, the lower crust is acoustically highly reflective, and in some areas of the Hebridean shelf contains structures whose trends are possibly of Caledonian or Scourian age. The reflective zone apparently terminates at the Outer Isles Thrust north of the Hebrides. A similar termination has not been observed south of the Hebrides.

3. The Moho is a fairly continuous reflector or group of reflectors, and is remarkably uniform in travel time, at about 8.5 s (≅ 27 km) below the foreland. Initial interpretations suggest it is apparently not significantly offset under the North Lewis or Minch Basins, nor under the Outer Isles Thrust. Confirmation of this conclusion must await more detailed modelling and migration experiments.

4. Structures such as the Outer Isles Thrust and Flannan Thrust appear to flatten into, and do not traverse, the lower crustal reflective layer, which therefore may be a zone of high strain.

5. The crustal reflection character of the foreland to the Caledonides differs from the areas of the foreland to the Appalachians studied with COCORP data, where Grenville crust is largely nonreflective.

6. Some of the basins on the Hebridean shelf are half-grabens formed by extensional reactivation of Caledonian thrusts. Conversely where these thrusts do not exist, the shelf has remained largely unaffected by extension.

7. The existence of the Outer Hebrides can be simply explained as an isostatic response to the Permian and Mesozoic normal faulting along the Minch Fault (reactivating the Outer Isles Thrust), which created the Minch and Sea of the Hebrides Basins.

Acknowledgments. Derek Abraham (BGS) kindly made available his preliminary gravity compilation of the Hebridean region used in Plate 4. Printer's proofs of unpublished BGS 1:100,000 scale tectonic maps of the Outer Hebrides were made available by Wally Mykura and Doug Fettes. GECO and GSI were very cooperative and helpful in the processing and reprocessing, respectively, of WINCH data. Funds for the reprocessing, and for participation in the BIRPS project by DKS, were provided by the UK Department of Energy.

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