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MOIST and the continuity of crustal reflector geometry along the Caledonian-Appalachian orogen

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SUMMARY: New aspects of the deep structure of the Scottish Caledonides are revealed by the Moine and Outer Isles deep seismic reflection traverse (MOIST). The Caledonian foreland is underlain by an easterly-dipping, strongly reflecting surface cutting through the Moho and traceable to more than 45 km depth. Thrusts within the foreland basement and Caledonian orogen have been reactivated as normal faults bounding half-grabens filled with sediments of late Palaeozoic to Mesozoic age. The Moine Thrust, which carries rocks of the orogen over Lewisian foreland, dips at 20–25° to the E on MOIST, and is either: (a) the westernmost of a series of easterly-dipping reflections (thrusts) which flatten or terminate at 17–20 km depth, or (b) a thrust lying further E which structurally overlies these easterly-dipping reflectors. By comparison with easterly-dipping reflections on COCORP lines in the northern and southern Appalachians the latter interpretation is preferred, implying that many of the easterly-dipping reflections on MOIST correspond to off-shelf metasedimentary rocks, with slivers of basement, stacked and imbricated against the Lewisian basement edge. Regional seismic refraction and conductivity data from northern Scotland suggest that regions of the Caledonian orogen have lower mid-crustal velocity gradients and higher conductivities than the foreland, which might be explained by this interpretation of the easterly-dipping reflections.

Despite similarities in crustal reflector geometries, there are important differences between the MOIST and COCORP lines, including (1) a remarkably continuous, relatively horizontal Moho seen on MOIST data at about 25 km depth, and (2) the sedimentary basins offshore from northern Scotland which have formed by reactivation under crustal extension of the easterly-dipping thrusts. Furthermore, it is probable that the easterly-dipping reflectors in these areas of the MOIST and COCORP lines were formed at different times in the early Palaeozoic.

Deep seismic reflection profiling is particularly well suited to the study of certain aspects of the evolution of continental crust, such as unravelling the geology of mountain chains and assessing the extent of crustal shortening by orogeny (e.g. Bally *et al.* 1966; Cook *et al.* 1979; Ando *et al.* in press). Following the success of the Consortium for Continental Reflection Profiling (COCORP) in the US, a similar project, the British Institutions Reflection Profiling Syndicate (BIRPS), has been set up by the Natural Environment Research Council to study the crust of the United Kingdom using deep seismic profiles. The first BIRPS line, the Moine and Outer Isles Seismic Traverse (MOIST) was recorded at sea just N of the coast of Scotland for the Institute of Geological Sciences. It crosses the northern margin of the Caledonian orogen, in an analogous position to COCORP profiles in the Appalachians (Figs 1 & 2). MOIST was shot and processed by Western Geophysical Company using a high-pressure airgun system (total capacity 905 in^3 at 4500 psi) and recording to 15 s (approximately 45–50 km depth). The data (Fig. 3) are spectacular, with clear reflections recorded from the Moho and possibly upper mantle (Smythe *et al.* 1982). In this paper we interpret the major features of the profile (Fig. 4), pointing out significant similarities with the COCORP Appalachian data, and extend a previous comparison of northern and southern Appalachian crustal reflector geometry (Ando *et al.* in press) to the Caledonides.

Geology of the Scottish Caledonides

The Caledonian foreland comprises Lewisian basement of highly deformed gneisses and granulites, metamorphosed at about 2700 Ma (Scourian) and 1750 Ma (Laxfordian; see Watson & Dunning 1979, and other articles in the same volume, for a useful review of the British Caledonides). The foreland is sheared in a major thrust zone, the Outer Isles Thrust (Fig. 2), one of the largest but least well-understood tectonic features of the British Isles (Sibson 1977). It extends for at least 150 km along strike, generally parallel to Caledonian trends, and is thought to be a Caledonian structure (Mendum 1979), although its age is not well constrained.

Foreland Lewisian is overlain by two cover sequences:

1. The Torridonian, consisting of sandstones and conglomerates (1100–1040 Ma; Smith *et al.* 1983) thought to have been laid down in an extensional, block-faulted environment; and

2. Cambrian-Ordovician quartzites and carbonates thought to have been laid down in shallow, subtidal

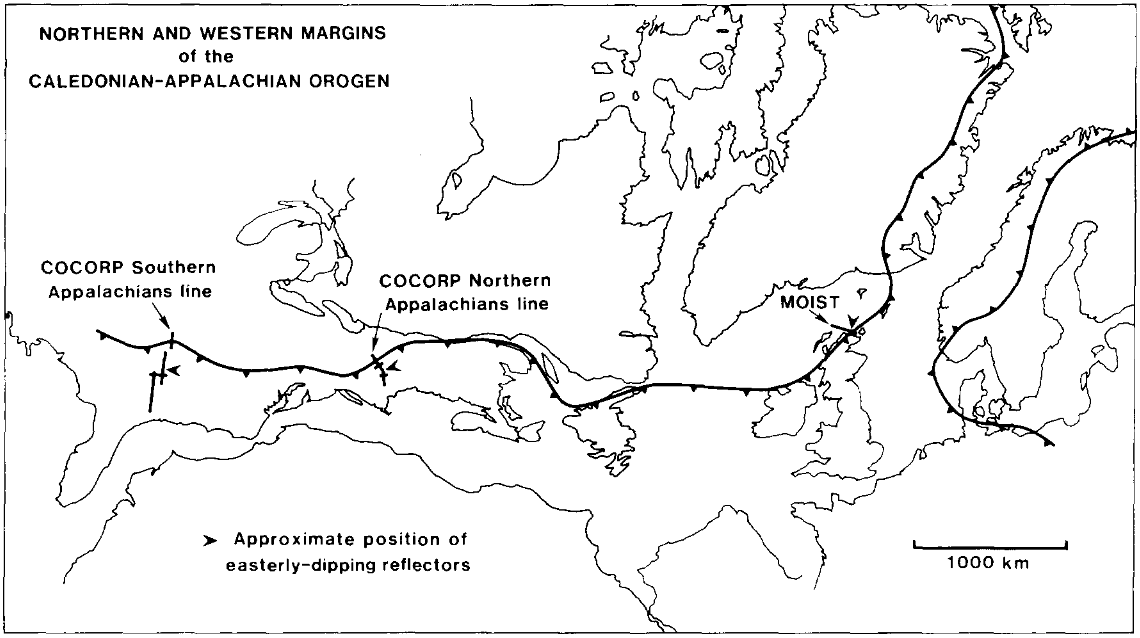


FIG. 1. Pre-drift reconstruction of Caledonian-Appalachian orogen (DKS, unpubl.). Barbed line corresponds to the western margin of the Blue Ridge in the southern Appalachians, the western margin of the Taconic allochthon in the northern Appalachians and the Moine thrust zone in Scotland. The variation in position of the easterly-dipping reflectors (thrusts) relative to these margins is probably due to varying degrees of overthrusting of the continental margin, and to subsequent erosion.

conditions on a continental shelf bounding the western margin of the 'proto-Atlantic' (Swett & Smit 1972).

The Moine succession (Johnstone 1975) is a complex sequence of psammites and pelites with metamorphic ages possible as old as Grenville (Brook *et al.* 1976), which were extensively heated and deformed during the Caledonian orogeny. The schists are thought to have been originally fluviatile or deltaic sediments. Lewisian-type inliers occur in the Moines either (1) as basement on to which some of the Moines were laid down, or (2) as thrust slices (Watson 1976). In conjunction with seismic refraction velocity data (discussed below), these occurrences are thought to imply that foreland basement underlies much of the Caledonian orogen.

Moine schists were carried over the foreland along the Moine Thrust zone (Fig. 2) during the later stages of the Caledonian orogeny. The Moine Thrust is the structurally highest thrust, and the zone below it consists of the intensely imbricated shelf sequence, including thrust slices of Lewisian and Torridonian, which were stripped off the autochthonous basement. Although estimates of the amount of shortening along individual thrusts range up to 60–70 km (Elliott & Johnson 1980), gravity and magnetic signatures suggest that autochthonous basement may only extend 20–30 km E of the Moine Thrust zone (Watson & Dunning 1979, p. 73). The thrust zone itself has been mapped in increasing detail ever since its discovery in 1883 (Peach *et al.* 1907), but attempts to project its structure to depth (e.g. Elliott & Johnson 1980; Coward 1980; Soper & Barber 1982) have lacked adequate subsurface control.

One of the key problems is the extent of foreland Lewisian basement under the orogen. Two groups of ideas have evolved, both based on surface mapping and on the interpretation of velocities obtained from the LISPB regional refraction survey (Bamford *et al.* 1978). Elliott & Johnson (1980) consider that the imbricated Cambrian-Ordovician succession under the Moine Thrust can be palinspastically restored using a set of 'rules' for thrust geometry developed in Mesozoic and Cenozoic thrust belts. Their reconstructions assume a uniformly thick 'layer-cake' stratigraphy in the dip direction. However, this is not the case in the southern Appalachians of the USA, where rocks of equivalent age and structural position have been studied using exploration seismic and well data (see for example, Harris *et al.* 1981, fig. 2). Elliott & Johnson's reconstructions, which correlate foreland basement with the basement slices caught up in the Moine Thrust zone, suggest that up to 100 km of shortening has occurred in the region of the Assynt window (Fig. 2). This implies that very gently sloping

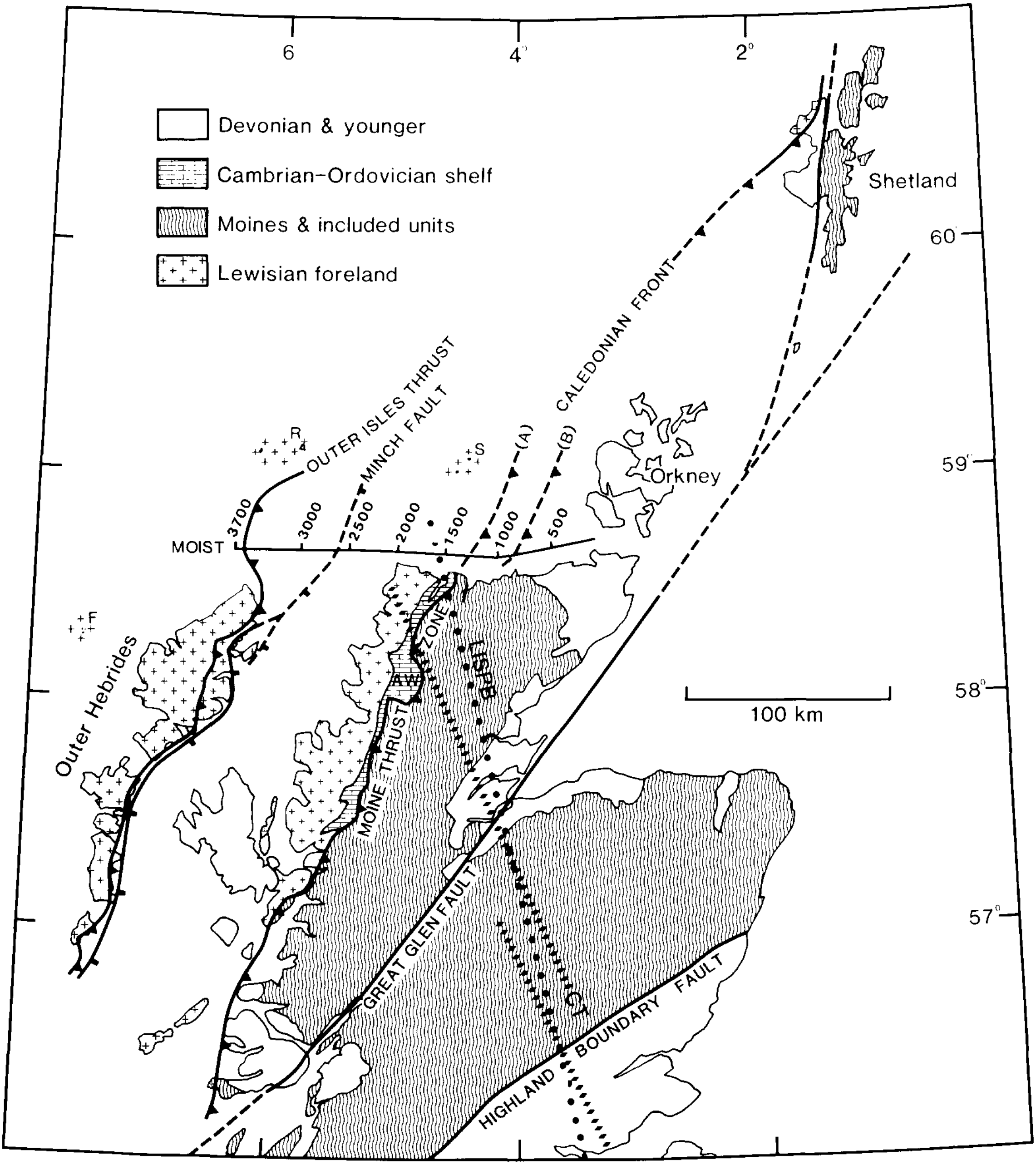


FIG. 2. Simplified geological map of northern Scotland with the location of MOIST. Shotpoints are marked along the line. Note that 'Moine and included units' includes Dalradian S of the Great Glen Fault and in Shetland. Alternative subcrops of the Moine Thrust zone offshore are marked (A) and (B); AW = Assynt Window. Geophysical traverses are CT = conductivity traverse (Hutton *et al.* 1980) and LISPB = LISPB explosion seismic profile (Bamford *et al.* 1978). Islands of Lewisian on horst blocks include F = Flannan Isles, R = Rona, S = Sule Skerry and Stack Skerry.

I.G.S.

WESTERN GEØPHYSICAL
C Ø M P A N Y Ø F A M E R I C A

ØFFSHØRE NØRTH SCØTLAND

W.G.C. CONTRACT	R20
PROCESSED IN LONDON DIGITAL CENTRE	OCT 1981
DATE SHOT	MAR 1981

RECØRDING DATA

BOAT

WESTERN ARCTIC	W.G.C. PARTY 103
PRIMARY NAVIGATION BY	SATNAV
MAP/SECTION LOCATION	CDP

SOURCE

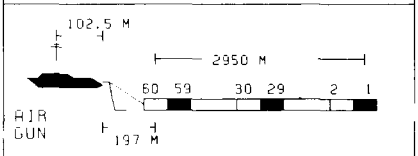
WESTERN HIGH PRESSURE AIRGUNS	16 GUNS
GUN DEPTH	12 M
VOLUME	905 CU.INS.
PRESSURE	4500 PSI
POPS PER KM	20
S.P. INTERVAL	50 M

INSTRUMENTS

AMPLIFIER	DFS V
FILTER	5.3-90 HZ
RECORD LENGTH	15 SECS
SAMPLE RATE	4 MS
FORMAT	SEG B

CABLE

3000M STREAMER	
NO OF GROUPS	60
HYDROPHONES	40 PER GROUP
GROUP INTERVAL	50 M
CABLE DEPTH	15 M



Q.C. FOR W.G.C. DMS

CØMMENTS

DATUM PLANE IS SEA LEVEL
A GUN AND A CABLE CORRECTION OF 18 MS HAS BEEN APPLIED IN THE FINAL DISPLAY.
COMPRESSION PULSES RECORD AS NEGATIVE NUMBERS ON TAPE AND PLOT AS TROUGHS (WHITE) ON PLAYBACK.

PRØCESSING SEQUENCE

PROCESSING SAMPLE RATE 4 MS

DEMULTIPLEX

RECEIVER ARRAY SIMULATION

3 GROUP RECEIVER MIX

PREPROCESSOR - D.B.S.

(A) COMMON DEPTH FAMILY GATHER
(B) GEOMETRIC SPREADING GAIN APPLIED
(C) DECONVOLUTION

TYPE	MIN. PHASE INVERSE FILTER
WINDOW LENGTH	9000 MS
MINIMUM PREDICTIVE LAG	32 MS
LENGTH OF FILTER OPERATOR	200 MS

(D) TRACE BALANCE ON OUTPUT

VELOCITY ANALYSIS

MATRIX VELANS

SOURCE ARRAY SIMULATION

5 SHOT WEIGHTED (1:2:2:2:1) SOURCE MIX

3000% N.M.O. STACK

FAR TRACE MUTE

D.A.S.

(A) TYPE	MIN. PHASE INVERSE FILTER
WINDOW LENGTH	3000-9000 MS
MINIMUM PREDICTIVE LAG	80 MS
LENGTH OF FILTER OPERATOR	200 MS

(B) TRACE BALANCE ON OUTPUT

TIME VARIANT FILTER

TIME (SECS)	L.C. (HZ.DB/OCT)	H.C.
0.004	10 / 18	40 / 48
3.000	6 / 12	32 / 36
11.000	5 / 12	25 / 24

FILTERS ARE INTERPOLATED IN TIME.

SCALING

RMS GAIN BY INCREASING ZONES OF 64 - 1024 MS

FIG. 3. MOIST seismic profile (pull-out opposite) after final processing, but unmigrated. Reflectors are displayed with reference to two-way travel time. No attempt (i.e. migration) has been made to place reflectors in their correct spatial location. Numbers along the top are shot-points (SPs); tick marks every 100 SP = 5 km. Recording and processing steps are summarized above. DBS, deconvolution before stack; NMO, normal move-out; DAS, deconvolution after stack. See Waters (1981, chs. 5 and 6) for a review of seismic reflection data acquisition and processing.


3700
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
100
TWO-WAY TIME (s)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

foreland basement once extended this far E under the orogen. Thin-skinned models for the Moine Thrust have also been proposed by Coward (1980), who applies similar arguments to the Cambrian-Ordovician rocks at Eriboll, on the N coast of Scotland, to those used by Elliott & Johnson further S. Additionally, Coward has suggested that both the Moine and Outer Isles thrusts flatten out at shallow depth, producing the 6.25 to 6.4 km s^{-1} seismic P-wave velocity boundary seen on LISPB at 8–10 km depth.

In contrast, a crustal duplex model has been postulated by Soper & Barber (1982), who consider that the thrust zone cuts through the crust at up to 45°, flattening out at the Moho. The LISPB data are used to support this model, together with the results of an electrical conductivity traverse (Hutton *et al.* 1980) and some palaeotemperature data.

The variety of crustal models mentioned above, all derived essentially from the same data, demonstrates that there are as yet few good correlations of geophysical parameters with lithology. The only well-constrained velocity-lithology data in the area (LUST: Hall 1978; Hall & Simmons 1979) refer to the Lewisian foreland. We suggest (in the discussion below) that these results do not have much significance in the orogen itself.

Results of the MOIST traverse

The MOIST profile displays spectacular reflections (Fig. 3), which not only constrain Caledonian structures, but also show how these have been reactivated during late Palaeozoic and Mesozoic extension. The Moho reflection, hoped for in view of the favourable results of previous wide-angle reflection and refraction experiments in the area (Smith & Bott 1975; Jacob & Booth 1977; Bamford *et al.* 1978), is well defined over the eastern half of the line, but in the W it appears to be disrupted or truncated by an easterly-dipping horizon, traceable from the middle crust (5–6 s, or 15–18 km deep) to the upper mantle (14 s, or over 45 km deep). The feature is not sideswipe (reflection from out of the plane of the section), as it can be identified at similar travel times on newly acquired BIRPS data. It has not yet been traced to the surface, but has been provisionally named the Flannan Thrust on the basis of its parallelism to the Outer Isles Thrust. Tests of reflector strength (relative amplitude displays) on MOIST show that this feature and the Moho are the strongest reflectors on the whole profile.

The western half

The Outer Isles Thrust intersects MOIST at about SP 3500 (Figs 2–4). Onshore it is interpreted as a thrust (Sibson 1977), but offshore seismic evidence suggests that it has been reactivated by listric normal faults (e.g. the Minch Fault, Fig. 2) bounding the western margins of half-grabens (Smythe 1982). The thrust is marked by a series of reflections dipping at about 25° (migrated) to 6.5 s—about 19–21 km depth (Fig. 3). Extrapolation to the base of the crust (at about 8.0 s) suggests that the fault coincides with a down-to-the-east (i.e. normal-faulted) Moho offset. The half-grabens probably contain Jurassic and Permo-Triassic (and possibly Torridonian) rocks about 4–5 km thick. Moho offset, however, is only 2–3 km, suggesting:

1. that the Moho on the E was originally displaced upwards by thrust movements, and that differential erosion of the upthrust crust took place before normal faulting shifted the Moho back down to the E; or
2. that the thrust (or its later normal-faulted trace) does not project through the Moho and, instead, that faulting took place along listric surfaces, with strain taken up in the lower crust (Fig. 4); or
3. that the present position of the Moho partially reflects adjustment during or after crustal extension and half-graben formation.

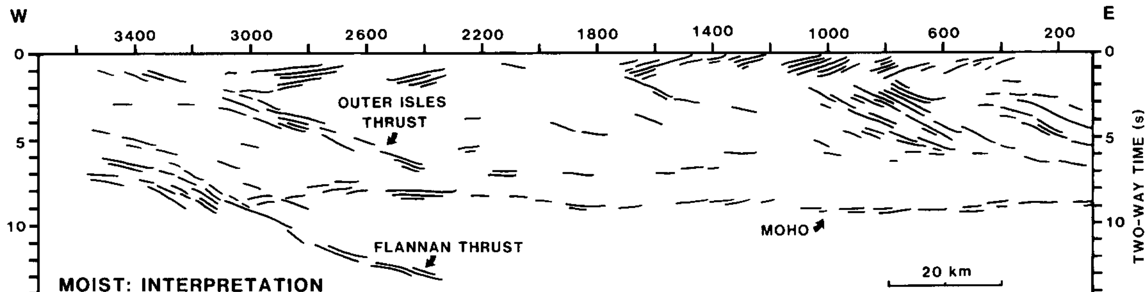


FIG. 4. Interpretation of principal reflectors on MOIST, prepared from unmigrated and migrated sections. Here, dipping reflectors are in approximately their correct spatial location, but depth conversion has not been applied. To correct two-way time in seconds to approximate depth in kilometres, multiply by three. Shot-points are numbered along the top.

The eastern half

Unless the Moine Thrust runs due E offshore to the Pentland Firth (Figs 2 & 5), it should intersect MOIST between SP 1200 and the eastern end of the line. It must therefore be one of the series of pronounced easterly and south-easterly dipping (20–25° migrated dip) reflections which characterize the eastern 60 km of the line, and which give the upper and middle crust under the orogen a quite different seismic character from that of the foreland (Figs 3 & 4). These reflections flatten or die out at around 17–20 km depth, and close to the surface are either directly overlain by westerly-dipping ?Devonian and Permo-Triassic sedimentary rocks occurring in half-grabens, or pass into acoustically transparent ('blank') zones beneath the half-grabens. The easterly-dipping reflections can be mapped along strike on a grid of commercial seismic lines recorded between 1970 and 1972 off the N coast of Scotland (Fig. 5; Smythe 1980). One of these lines is reproduced in Fig. 6. These reflections define lozenge-shaped packages, within which there are subsets of concordant or subparallel reflections. These subsets are not well seen on MOIST, but the boundaries to the lozenges are well defined (*cf.* Figs 3 & 6), perhaps because of the somewhat different data processing. The reflector subsets are discordant with the boundaries of the lozenges, which we interpret as a series of imbricated thrust packages, trending roughly N–S and dipping at 20–25° to the E. The origin of the reflector subsets is not known, but they could be (1) surfaces of shearing that developed into the imbricate lozenges, or (2) originally flat layering such as sedimentary bedding, which has been tilted within the lozenges. The tilting of this presumed bedding is in the wrong sense to have resulted from normal faulting along the easterly-dipping reflectors, but could have arisen from stacking and imbrication along thrusts (the lozenge boundaries). Note that the bedding-like reflector subsets are not observed below the Lewisian foreland. The later normal faults bounding the half-grabens are controlled by the position of these easterly-dipping thrusts (Figs 3 & 4), so that the original dip of the thrusts will have been reduced somewhat by this later normal movement.

Following summaries of geophysical data interpretations in northern Scotland, and of COCORP and related data in the Appalachians, we shall discuss two possible interpretations of the Moine Thrust. Case A is the simplest projection of structures offshore from their known position onshore to MOIST. The Moine Thrust is then the westernmost of our mapped easterly-dipping reflectors (Fig. 7). In case B the Moine Thrust is one of the easterly-dipping reflections lying considerably further E. This would require the Moine Thrust to swing sharply eastward, by about 25 km, between its position onshore and MOIST (Fig. 2). The two cases cannot be tested with the commercial seismic data (Fig. 6), because in the region close to the coast where the critical test of the two possibilities could be made by matching reflectors with surface geology, the few lines available are of poor quality.

Reinterpretation of refraction and conductivity data in northern Scotland

Changes in crustal structure at the north-western margin of the Caledonian orogen have been suggested by the results of several regional refraction profiles; however, the orogen has been rather poorly sampled by these lines in comparison to the foreland. The NASP experiment (Smith & Bott 1975) gave first arrivals with P-wave velocities of about 6.1 km s^{-1} over foreland basement, 6.5 km s^{-1} at depths of 2–16 km, and a Moho arrival (8.0 km s^{-1}) indicating a depth of 26 ± 2 km. W of the Outer Hebrides the HMSE line (Bott *et al.* 1979) found the Moho at similar depths, but smaller-scale lines in the same region show that the top of the Lewisian basement has velocities varying from 5.1 to 6.4 km s^{-1} (Jones 1981).

The LISPB regional refraction profile (Bamford *et al.* 1978) runs from the foreland into the orogen, crossing MOIST at about SP 1500 (Fig. 2). It has been interpreted in terms of a three-layered crust under northern Britain:

1. upper crust (to about 8–10 km depth) with P-wave velocity about 6.1–6.2 km s^{-1};
2. middle crust (to about 18–20 km depth) with velocity about 6.4 km s^{-1}; and
3. lower crust (to about 28–30 km depth) with velocity about 6.7–7.3 km s^{-1}.

Thus LISPB and NASP appear to indicate that the upper two crustal layers (as defined by regional refraction) have rather similar velocities both in the foreland and the orogen.

Laboratory studies and *in situ* measurements of foreland Lewisian rocks (Hall & Al-Haddad 1976; Hall & Simmons 1979) suggest that the upper and middle crustal layers here are probably (a) mixed metamorphic rocks in amphibolite or lower-grade facies, with granites, overlying (b) mixed pyroxene-granulite facies rocks of overall intermediate composition. However, remodelling the LISPB data using synthetic seismograms and allowing for lateral variations (Cassell 1982; Cassell *et al.* in prep.) suggests that, whereas the upper–middle crustal boundary is fairly uniform in northern Britain, the middle–lower boundary is discontinuous. SE of the Moine Thrust zone the boundary is defined by a substantial velocity increase, from 6.45 to 7.0 km s^{-1}, whereas in the foreland the same boundary is poorly defined, corresponding only to a negligible velocity increase, from about 6.7 to 6.8 km s^{-1}. Thus the mid-crust layer below the part of LISPB which lies along strike from

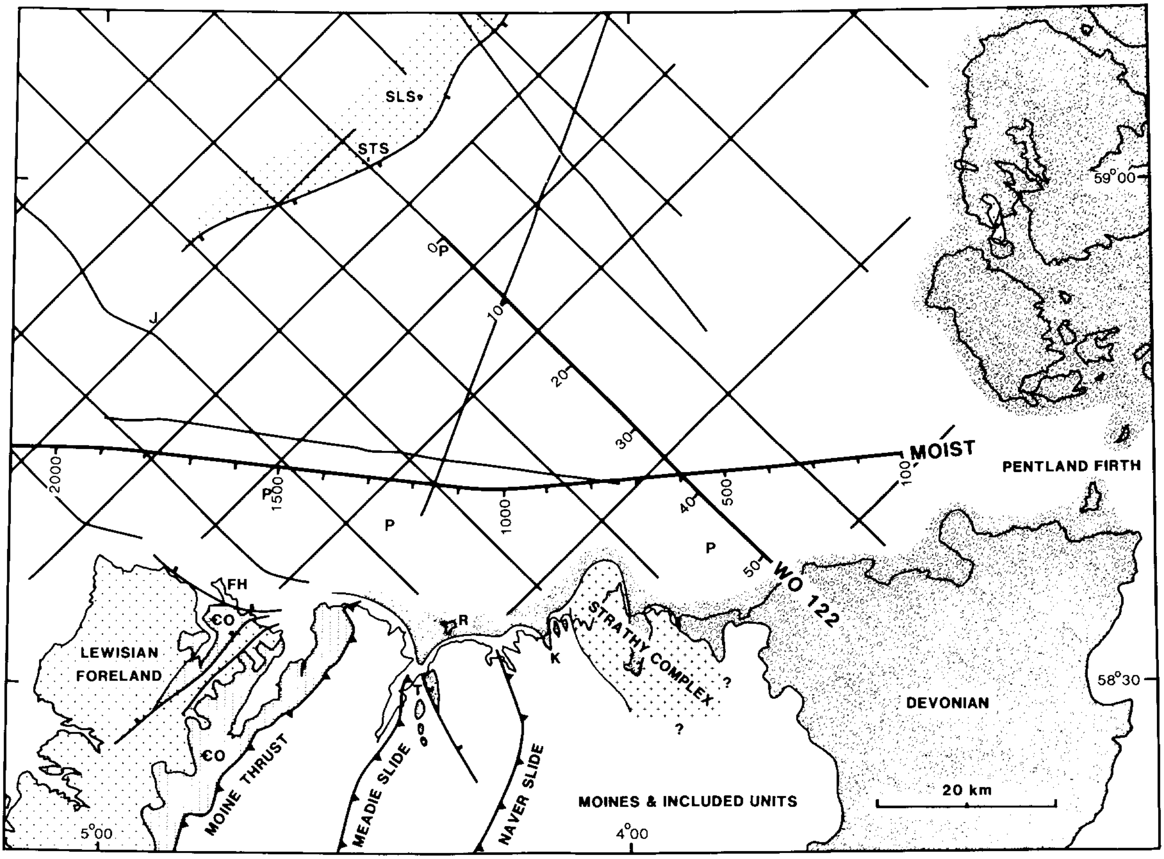


FIG. 5. Seismic line location map of the W Orkney area. Heavier lines are MOIST (Fig. 3), annotated with shot-points, and GSI WO 122 (Fig. 6), with tick-marks every 10 km. Extrapolation of the major onshore basement structures offshore is complicated by the cover of Devonian sediments, which extend locally onshore and which are themselves covered offshore by younger rocks proved in shallow boreholes (P = Permo-Triassic; J = Jurassic). The Strathy Complex is an inlier of Lewisian-like rocks. €O, Cambrian-Ordovician; STS, Stack Skerry; SLS, Sule Skerry; FH, Faraid Head; R, Roan Islands; K, Kirtomy; T, Tongue.

the easterly-dipping reflections on MOIST has a much lower velocity gradient than the foreland crust, but the middle to lower crustal boundary is much more pronounced (B. R. Cassell pers. comm.). This pronounced boundary may correspond to the surface, at 17–20 km depth, at which the easterly-dipping reflectors seen on MOIST flatten out. Since the seismic crustal structures of the foreland and orogen are therefore dissimilar, both on the gross scale (as defined by refraction) and on the fine scale (as defined by reflection character), we conclude that the velocity studies of the foreland (Hall & Al-Haddad 1976; Hall & Simmons 1979) must be applied with caution to the orogen. *In situ* measurements and laboratory studies of Moine and Dalradian rocks are required to clarify this point.

Magnetotelluric and magnetovariational experiments (Hutton *et al.* 1980) suggest that the region of the northern Scottish crust possibly containing easterly-dipping reflections may have a high conductivity relative to the Lewisian foreland. Although the data are sparse, with poor control on the location of horizontal and vertical variations (Hutton, pers. comm. 1982), they do suggest that the conductivity of Lewisian foreland is of the order of $10^{-4}\,\mathrm{S\,m^{-1}}$, whereas conductivities E of the Moine Thrust zone, below depths of about 8 km, are of the order of $10^{-3}\,\mathrm{S\,m^{-1}}$. Above 8 km depth, conductivities are similar to those of the Lewisian foreland. The lower boundary of the high conductivity zone in Hutton *et al.*'s models lies within the upper mantle, i.e. considerably deeper than the base of the easterly-dipping reflections. This could be an artefact of the modelling (Hutton, pers. comm. 1982), and although more data are needed to constrain the boundaries, it is possible that the north-western boundary of the high

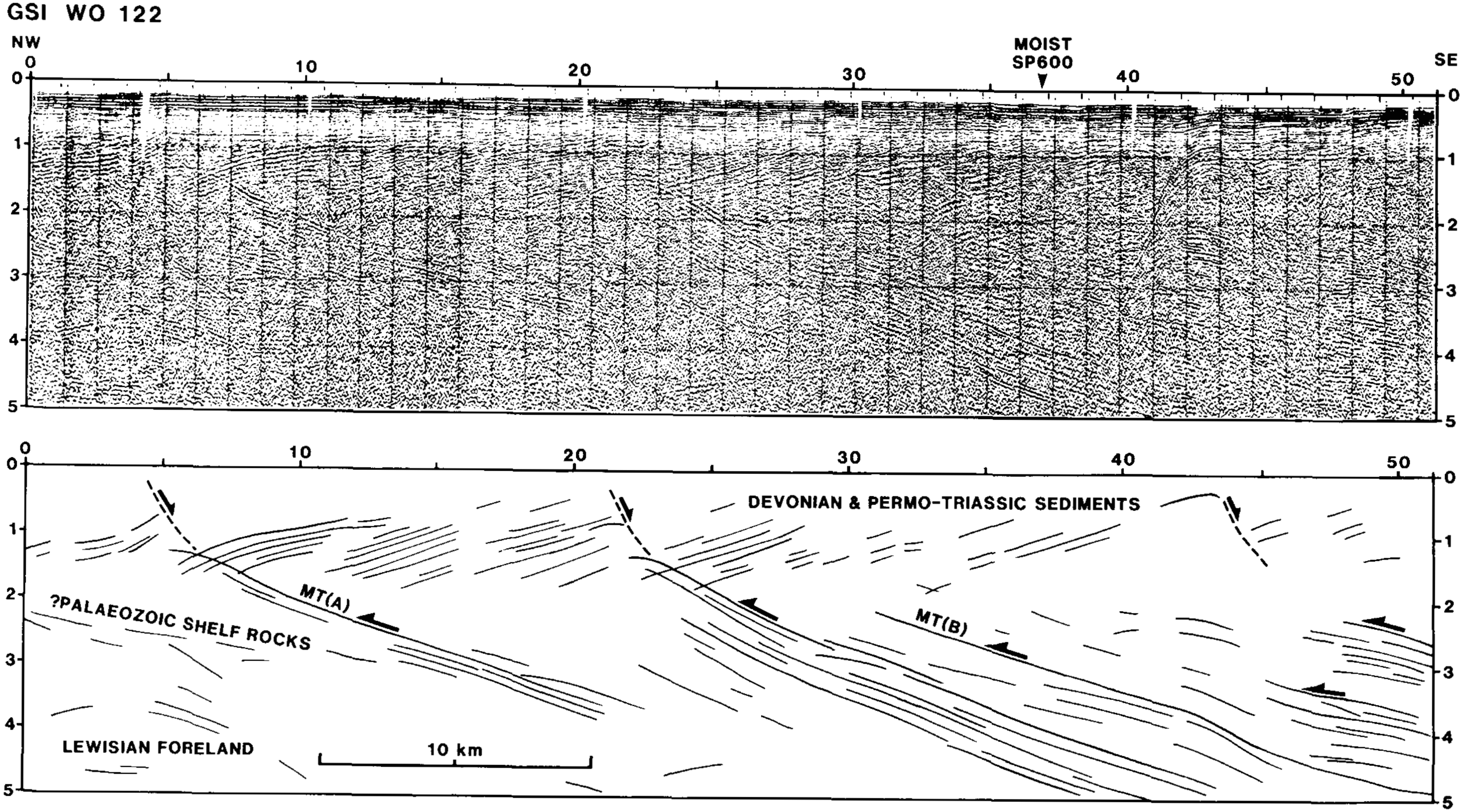


FIG. 6. GSI seismic profile WO 122, obtained in 1973. Horizontal scale is in kilometres. This section (located in Fig. 5) illustrates the well-layered reflectors within the easterly-dipping thrust slices, in contrast to MOIST where the thrusts stand out as the major reflectors. The sediments lie in westerly-tilted half-grabens, the bounding normal faults of which (dashed lines) have reactivated the earlier thrusts.

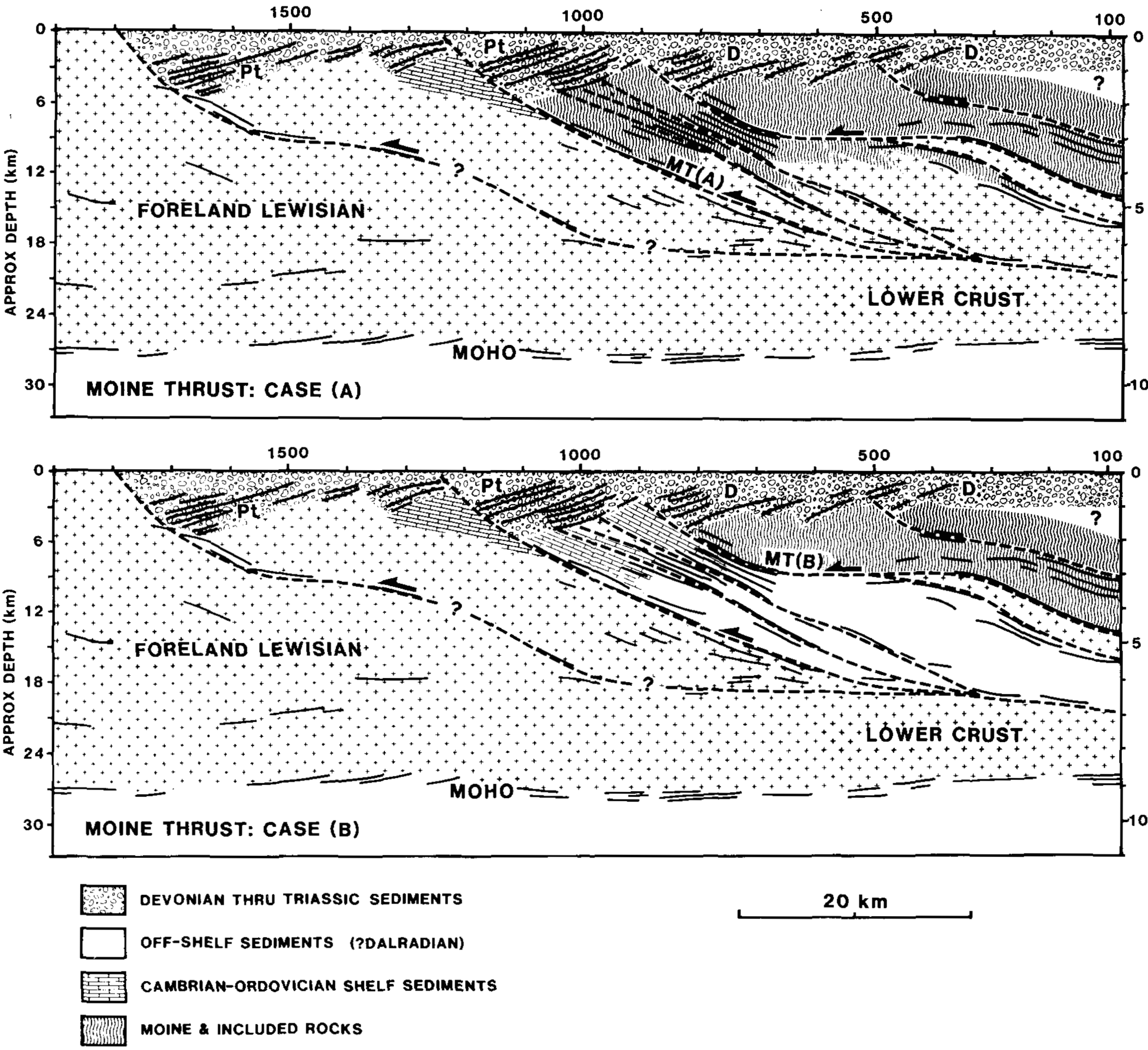


FIG. 7. Two possible interpretations of the Moine Thrust. Reflectors are indicated by solid lines (Fig. 4), picked from migrated and unmigrated data. Geological interpretation uses data from along strike. Faults (dashed lines) are simplified on the eastern half of the line. D, Devonian; Pt, Permo-Triassic. Note that the depth conversion, assuming a constant crustal $V_P = 6\ \mathrm{km\ s^{-1}}$, exaggerates depths of the sedimentary basins by a factor of 1.5 to 2. MT(A) and MT(B) are alternative positions of the Moine Thrust discussed in the text.

conductivity zone corresponds to the region of easterly-dipping reflectors seen on MOIST.

COCORP data in the northern and southern Appalachians

COCORP lines which can be directly compared with MOIST have been recorded in the southern Appalachians, running from the foreland Valley and Ridge province to the coast (Cook *et al.* 1979, 1981), and in the northern Appalachians (Ando *et al.* in press), running from the Adirondack mountains E into New Hampshire (Figs 1 & 8).

In the southern Appalachians the COCORP lines show that early Palaeozoic sedimentary rocks, correlative with those of the Valley and Ridge, can be traced south-eastward as a series of sub-horizontal reflections varying in depth from 5 to 10 km, under crystalline rocks of the Blue Ridge and Inner Piedmont, to the western edge of the Kings Mountain Belt (Cook *et al.*

1979). Further E these horizontal reflections pass into a zone, lying between 10 and 18 km depth, of easterly-dipping (20–25°) reflections, which in turn pass into a zone of sub-horizontal reflections between 15 and 18 km depth (Fig. 8). These easterly-dipping reflections, which have low stacking velocities and which occur in a region of low refraction velocities (Long 1979), may be from off-shelf metasedimentary rocks upthrust and imbricated against the late Precambrian–early Palaeozoic continental margin (Cook & Oliver 1981). They apparently lie basinward of the approximate position of the continental margin or carbonate bank edge obtained by palinspastically restoring folded Valley and Ridge rocks; gravity and magnetic data are also consistent with a buried basement edge (Cook & Oliver 1981). Timing of the deformation of the buried basement edge is not clear, but probably occurred during one or more of the Taconian (Ordovician), Acadian (Devonian) and Alleghenian (Permo-Carboniferous) orogenies.

Conductivity data provide further constraints on interpretations of the southern Appalachians. A commercial magnetotelluric survey shows that the zone of sub-horizontal reflections under the Inner Piedmont and Blue Ridge seen on COCORP lines coincides with a region of high conductivity (F. A. Cook, pers. comm. 1981). Moreover, the easterly-dipping reflections also lie in a region of high conductivity (over 10^{-2} S m^{-1}; Thompson 1982).

In the northern Appalachians (Fig. 1) COCORP lines cross the Beekmantown, Black River and Trenton Groups, which are the facies-equivalents of

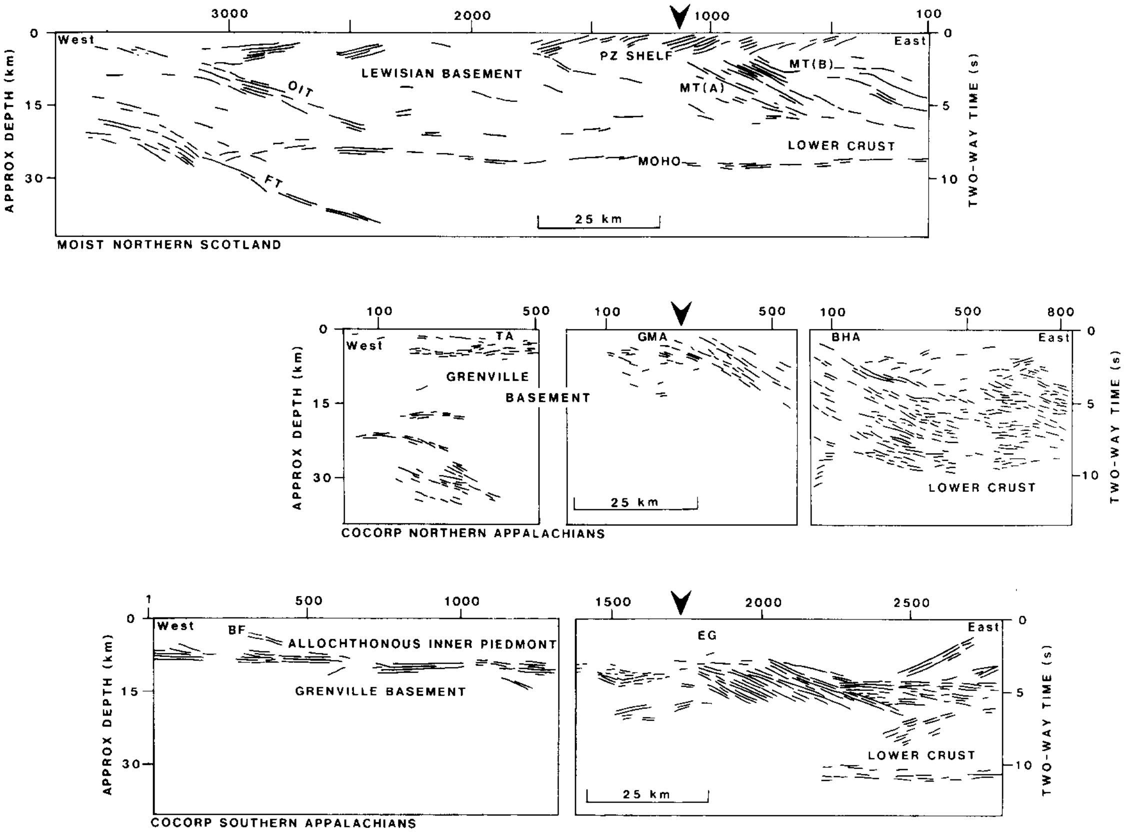


FIG. 8. Comparison of MOIST and COCORP Appalachian data. Arrows mark western limit of easterly-dipping reflectors (thrusts) outboard (E) of the foreland (Lewisian and Grenvillian basement). MOIST and the southern Appalachian data are geometrically the most similar; the northern Appalachian thrusts are slightly steeper and continue to greater depths. 'Lower crust' on all three lines marks relatively reflection-free area, above which the easterly-dipping reflectors flatten out. OIT, Outer Isles Thrust; FT, Flannan Thrust; MT(A) and MT(B), two possible positions of the Moine Thrust; TA, Taconic allochthons; GMA, Green Mountain anticlinorium; BHA, Bronson Hill anticlinorium; BF, Brevard Fault; EG, Elberton granite. Northern Appalachian data are from Ando *et al.* (in press).

the northern Scottish Cambrian-Ordovician shelf carbonates. These are interpreted as shelf sequences deposited on Grenville (about 1000 Ma) basement (Rodgers 1968). The profile crosses slivers of Grenville basement (for example, the Green Mountains and the Chester Dome), which have been thrust westwards over the shelf carbonates (Ratcliffe & Harwood 1975; Ratcliffe & Hatch 1979; Ando *et al.* in press). The shelf to off-shelf transition occurs on the eastern margin of the Green Mountains, where the Lower Palaeozoic shelf edge was imbricated and transported westwards during the Taconic orogeny (Rodgers 1968). This region is underlain by easterly-dipping (30–35°) reflections which appear to flatten at about 30 km depth, and which are interpreted as a zone of complex deformation associated with a large thrust ramp bringing Precambrian basement to higher levels (Fig. 8; Ando *et al.* in press). The age of the thrusting is not known and could have occurred late in the Taconian orogeny, or could be related to Acadian deformation.

Interpretations of MOIST

The lozenge-shaped thrust-slices offshore from northern Scotland must have been formed in the later stages of Caledonian deformation. The reflectors bounding these lozenges can be traced on MOIST and the commercial seismic data from subcrop below sedimentary rocks in the half-grabens to more than 5–6 s (15–18 km depth), with fairly uniform dip and no apparent folding. If case A (Fig. 7) is the correct interpretation, many late-Caledonian thrusts must be present onshore, corresponding to the easterly-dipping thrusts E of, and structurally higher than, the Moine Thrust. Whereas thrusts and slides of several ages, some of which interleave Lewisian basement and Moine schist, do occur in the Moines, they are generally considered to be of pre- or early Caledonian age and subsequently folded (Mendum 1979), so that case A requires a re-interpretation of onshore structures. Case A indicates that the Moine Thrust flattens at 17–20 km depth, and that Moine sedimentary rocks were deposited, in approximately their present position relative to the foreland, in an ensialic basin on Lewisian crust. Subsequent overthrusting along the Moine Thrust zone was, therefore, of limited extent. This interpretation also predicts that the metamorphic layering in the Moines will give rise to well-defined layered reflections, which should be possible to test with future BIRPS lines on land. Case A implies that, although crustal reflector geometry is similar to the Appalachians (Fig. 8), the geological histories of the two areas are rather different.

A variation of case A has been suggested by R. W. H. Butler (pers. comm. 1982), who considers that the imbricated Cambrian-Ordovician rocks in the Moine Thrust zone at Eriboll on the N coast of Scotland can be palinspastically reconstructed (using the same assumptions as Elliott & Johnson 1980), to show them originally occupying a wide shelf extending some 60 or 70 km E of the present position of the Moine Thrust zone. He assumes that foreland basement directly underlay this carbonate shelf, and that the easterly-dipping thrusts are intra-basement thrusts which were active after the phase of thin-skinned shortening and imbrication of the cover rocks. Although the seismic data do permit this interpretation, it does not account for the 'well-layered' reflectors (for example, Fig. 6) seen within the lozenge-shaped thrust slices—such distinctive seismic layering is not seen elsewhere on the Lewisian foreland.

Case B (Fig. 7) implies that the subsets of concordant internal reflections must be from layered rocks below Moine schists. This structural position is occupied onshore by the shelf carbonate sequence, so that these rocks, or their basinward equivalents, may be present below MOIST. Case B is attractive because it suggests close similarities in the geological development of the Appalachians and the Caledonides. By analogy with the Appalachians, most of the easterly-dipping reflections may be from a sequence of Palaeozoic off-shelf metasedimentary rocks imbricated with slices of basement. This interpretation is possibly more consistent with the 'well-layered' seismic character of the concordant reflection sequences lying within the easterly-dipping lozenges. Although there is no direct evidence on the mainland of northern Scotland for these proposed off-shelf sequences, extrapolation along strike N to Shetland using commercial seismic data, magnetic and gravity data suggests that the Dalradian metasedimentary rocks found there (Flinn *et al.* 1979) could be analogous. Furthermore, Dalradian rocks are thrust over Lewisian foreland along a possible extension of the Moine Thrust 350 km to the SW on the island of Islay. Magnetic data there suggest that basement exposed in the foreland lies at 15–20 km depth under the orogen (Westbrook & Borradaile 1977), perhaps equivalent to the depth at which the easterly-dipping reflections on MOIST flatten out (17–20 km). Dalradian rocks were laid down above Moine rocks in a fairly stable late Precambrian–early Cambrian trough, which subsequently foundered (Harris & Pitcher 1975), and parts of the Dalradian have previously been equated with the Lower Palaeozoic shelf sequence (Harris & Pitcher 1975, p. 73). If case B is correct, then crust now E of the dipping reflectors and underlying the Moines was once separate from the Lewisian foreland. The combination of the dipping reflectors and this crust corresponds to Hutton *et al.*'s (1980) high conductivity zone, and has a middle crustal layer with a fairly low velocity gradient with respect to rocks at similar depths in the foreland Lewisian (Cassell *et al.* in prep.), as discussed above.

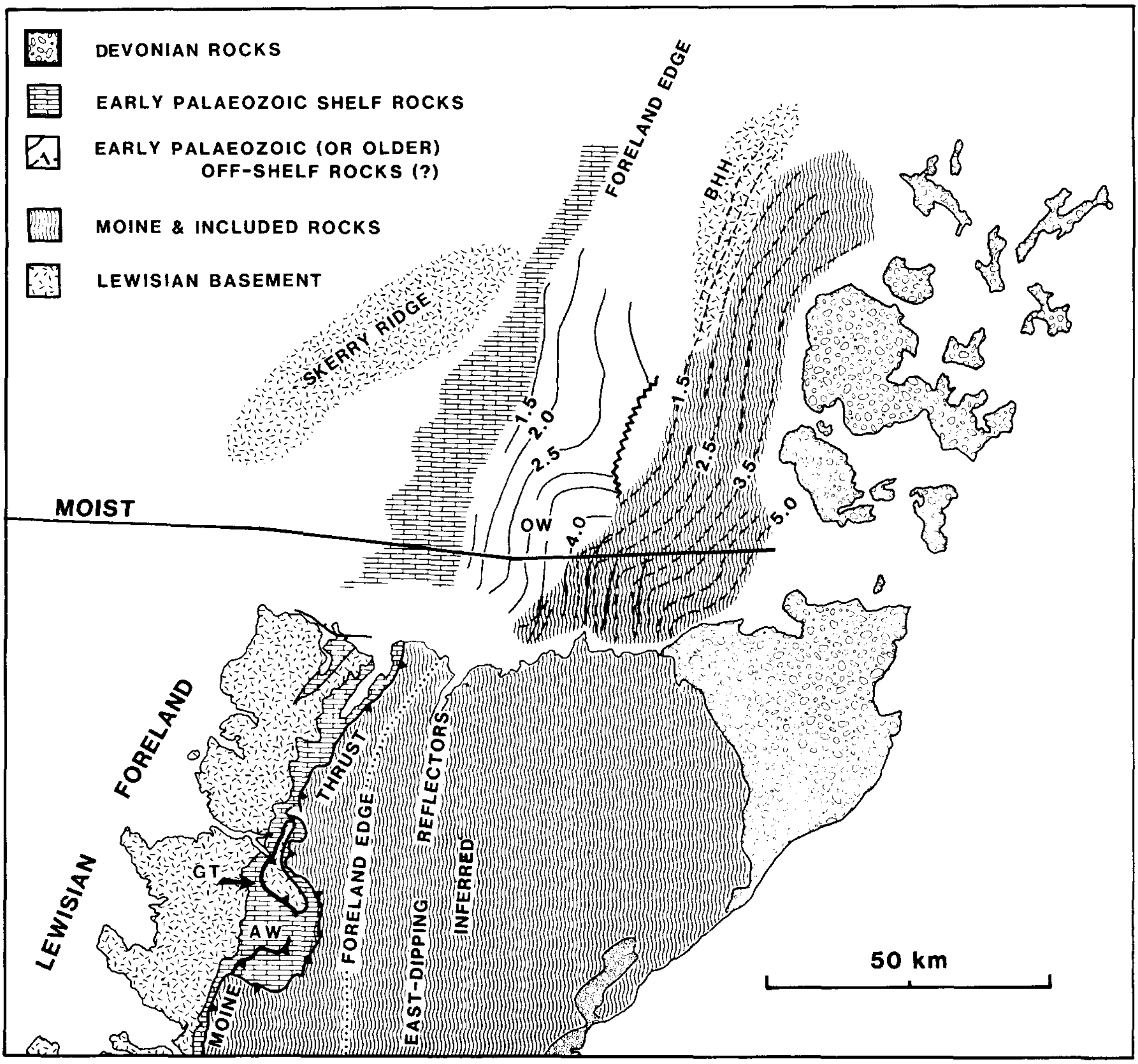


FIG. 9. Offshore and onshore geometry of the Moine Thrust zone with the case B hypothesis. The zone onshore is depicted simplified; 'Early Palaeozoic shelf rocks' unit is highly imbricated. The subcrop of Moines offshore is shifted 30 km eastward to form the Orkney window (OW). This can be explained either by an E–W trend of the thrust just offshore, or by the effect of late extension recorded by the sedimentary half-grabens (*cf.* Fig. 6). Further N the regional NE–SW trend is resumed. Dashed contours are in seconds of two-way time to the Moine Thrust (multiply by about 2.5 to get approximate depth in kilometres). Solid contours are on the most westerly (lowest) thrust bounding the zone of easterly-dipping lozenge-shaped thrust packages (see text). These lozenges lie E of the 'foreland edge' boundary; offshore this boundary is interpreted from seismic reflection data, but onshore it is taken from aeromagnetic data and is therefore tentative (see also Watson & Dunning 1979, fig. 3). Note that the Assynt window (AW) exposes the Moine Thrust zone where it overthrusts Lewisian basement, whereas the Orkney window reveals structure within the root zone outboard from the foreland edge. Thrust slices of Lewisian basement, for example, above the Glencoul Thrust (GT), have been plucked off the foreland edge; this may also be the case with the Brough Head High (BHH) above the Moine Thrust. Most of the offshore geology shown is of subcrop below Devonian and Permo-Triassic sedimentary basins 2–3 km deep.

Case B implies that there is a large structural window through the Moine Thrust offshore from northern Scotland (the Orkney window), perhaps similar to the well known Assynt window onshore (Figs 2 & 9; Peach *et al.* 1907). The southern margin of this window lies very close to the present coastline, and perhaps controls its location. However, there are dissimilarities between the Assynt window and the Orkney window, because they lie in different positions relative to the edge of foreland and reveal different structural levels of the Moine Thrust zone. The Assynt window exposes the zone where it has a shallow dip (8–15°) and overthrusts autochthonous Lewisian foreland, which is covered by a thin Lower Palaeozoic shelf sequence (Fig. 9). Offshore, below MOIST, the eastern limit of the basement edge lies further W, but the Moine Thrust has stepped eastward, so that the Orkney window reveals the thrust system root zone: that is, the deeper part of Watson & Dunning's (1979, fig. 4) orogenic front. The root zone, which we suggest developed at the Palaeozoic edge of the Lewisian basement, is characterized by more steeply-dipping (20–25°) thrusts which flatten out at depth, so that only the upper 20 km of crust was sheared and deformed in the Caledonian orogeny. The eastern edge of the Lewisian foreland basement (defined onshore by aeromagnetic data and offshore by seismic data) should not be confused with the eastern edge of the Lower Palaeozoic shelf sequence, which is derived by palinspastically reconstructing the imbricated shelf rocks. At the N coast of Scotland the edge of foreland basement lies 5–10 km E of the Moine Thrust, whereas the shelf sequence edge lies possibly more than 30 km east of the thrust (Butler 1982). If these two inferences are both correct, then the shelf sequence eastward of the basement shelf edge must have been laid on top of a thick sequence of off-shelf rocks (possibly Dalradian).

By analogy with the northern Appalachians, case B implies that slices of Lewisian basement caught up in the Moine Thrust zone, for instance along the Glencoul Thrust in the Assynt window (Peach *et al.* 1907) and the Brough Head High in the Orkney window (Fig. 9), are structurally equivalent to the Grenville basement inliers which have been sliced off the continental margin and transported landwards over the shelf (Ratcliffe & Hatch 1979; Ando *et al.* in press). Taking the Appalachian analogy further, case B also implies that the easterly-dipping reflectors flatten out above crust underlying an ocean basin—either transitional or oceanic crust. The southerly extent of such crust is as yet unknown, but its presence below the Scottish mainland would have important implications for the isotopic interpretations of igneous rocks S of the Moine Thrust, since it implies a lower crust of oceanic affinities. The ophiolite sequence of unknown age exposed in the Shetlands (Flinn *et al.* 1979) can perhaps be explained as obducted remnants of this oceanic crust.

The interpretations that we have proposed can be tested. Seismic experiments over exposed Moine schists, to determine whether layered reflections are seen, might discriminate case A from case B. More palaeomagnetic data might constrain the date of separation of the Moines and Lewisian foreland, before Moine Thrust zone formation, and hence the extent of the basin within which the postulated off-shelf sedimentary rocks were formed.

Implications of MOIST for interpretations of orogenic belts

Some of the inferences we have drawn from the MOIST profile may be relevant to the study of the margins of other orogenic belts.

Intra-foreland thrusting

Although Lewisian basement is regarded as the foreland to the Caledonian orogen, it did not necessarily remain a rigid, unfractured block. The Outer Isles and Flannan Thrusts (both assumed to be Caledonian in age because of their similar dip and strike to the demonstrably Caledonian thrusts) presumably formed as the foreland fractured under the same orogenic stresses that were causing the Moines to override the foreland further E. Such fracturing would probably have become more pervasive if the crustal shortening had continued. In the Appalachians the COCORP data show little evidence for foreland fractures, but perhaps this is simply because such features have not yet been resolved. The continuity, penetration of the upper mantle and reflection strength of the Flannan Thrust suggest that it may be the most profound Caledonian structure yet discovered. Whether or not this proves to be the case, it is clear that surface mapping alone (however detailed and precise, as in Scotland) is incapable of revealing all the fundamental structures of an orogenic belt.

The existence of intra-foreland thrusts makes the definition of 'orogenic front' rather ambiguous. In Fig. 1 the northern margin of the orogen is taken to be the present-day limit of allochthonous rocks. This results in an S-shaped bend between Shetland and Greenland, which might be removed by taking the margin of the orogen as the limit of intra-foreland fracturing.

Thrust geometry

The Flannan Thrust, Outer Isles Thrust and the easterly-dipping lozenges all dip at about 25–35°; over the length of MOIST there is little evidence for thrust dips progressively steepening into the centre of the orogen (although some of the present-day dips may have been modified by later crustal extension).

Whereas the thrusts bounding the lozenges flatten out at 17–20 km depth, the Outer Isles and Flannan Thrusts do not flatten at all within the depth ranges to which they have been imaged, suggesting that faults may penetrate deeper into the continental lithosphere with distance into the foreland. However, the Flannan Thrust, the only reflector which definitely penetrates the upper mantle, has not yet been traced to the surface.

Related thrust and extension faulting

Post-thrusting upper crustal extension has modified many of the structures along MOIST, and half-grabens filled with ?Devonian and Permo-Triassic red beds are controlled by normal faults which have reactivated the Caledonian thrusts. Similar later crustal extension is not apparent over most of the COCORP Appalachian data. The presently-observed dips of the thrusts offshore from northern Scotland are less than the original dips (around 35°) at the time of thrusting, as they have been reduced by the rotational component of the later normal faulting.

About 25 km of upper-crustal extension in a NW–SE direction has taken place between the Stack Skerry–Sule Skerry ridge and the mainland of Scotland (Fig. 6; our unpublished work), by the relaxation of the thrusts bounding the easterly-dipping lozenges, although no comparable extension has been identified onshore. It is significant that the offshore extension has been caused by the reactivation of earlier thrusts, because it explains the preponderance in this region of westerly-tilted half-grabens. This relationship could be applied elsewhere along the western margin of the Caledonian orogen to predict (1) the location of basins, where the orogenic margin structure is known, or, conversely, (2) to define the locations of buried thrusts beneath a cover of half-graben-controlled sediments.

The recognition of early thrusts being reactivated as later normal faults complements the inference from earthquake studies in the Zagros orogenic belt that early normal faults can be reactivated as later thrusts (Jackson *et al.* 1981). Clearly, reflection studies of buried basement can provide valuable information on the structure and evolution of the overlying sedimentary basins.

The Moho

The Moho on MOIST is remarkably continuous and relatively flat, although it has been poorly imaged on COCORP data in the Appalachians. We do not know why its character offshore from northern Scotland is so distinctive, but speculate that it may be related to the upper-crustal extension. For example, on land the Moine Thrust zone has an easterly dip of some 8–12°, usually attributed to a post-Caledonian effect (Elliott & Johnson 1980), but the regional tilt is not apparent on the Moho below MOIST. This implies that the present-day Moho should not be regarded as a constraint on models of Caledonian tectonics.

Conclusions

1. MOIST contains reflection sequences whose geometry is remarkably similar to those observed on parts of COCORP profiles recorded in the northern and southern Appalachians, and which in all three areas lies basinward from shelf carbonate sequences. This implies continuity in deep crustal structure along parts of the Caledonian-Appalachian mountain chain, although tectonic events were probably diachronous.
2. Conductivity data in Scotland and the southern Appalachians are also comparable. Together with the seismic refraction data, these are consistent with the interpretation that easterly-dipping reflections on MOIST are from relatively high conductivity, relatively low (refraction) velocity-gradient, off-shelf metasedimentary rocks imbricated against the Lewisian basement edge. The Moine Thrust overrides this sequence (case B).
3. Despite these similarities, the case A interpretation of MOIST, in which the Moine Thrust underlies the easterly-dipping thrusts, is also consistent with data from northern Scotland as they are presently understood.
4. Although case B is our preferred interpretation, major differences between the Caledonides and the Appalachians include the possibly Grenville-aged metasedimentary rocks (Moine schists) and the relatively flat and shallow Moho in the former area.
5. These data show that extensional structures N of the coast of Scotland were formed by reactivation of Caledonian thrusts, thus illustrating the importance of the study of basement structures in understanding sedimentary basin formation.

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References

ANDO, C. J., COOK, F. A., OLIVER, J. E., BROWN, L. D. & KAUFMAN, S. in press. Crustal geometry of the Appalachian orogen from seismic reflection studies. *Mem. geol. Soc. Am.*

BALLY, A. W., GORDY, P. L. & STEWART, G. A. 1966. Structure, seismic data and orogenic evolution of Southern Canadian Rocky Mountains. *Bull. Can. Pet. Geol.* **14,** 337–81.

BAMFORD, D., NUNN, K., PRODEHL, C. & JACOB, B. 1978. LISPB-IV. Crustal structure of northern Britain. *Geophys. J. R. astron. Soc.* **54,** 43–60.

BOTT, M. H. P., ARMOUR, A. R., HIMSWORTH, E. M., MURPHY, T. & WYLIE, G. 1979. An explosion seismology investigation of the continental margin west of the Hebrides, Scotland, at 58°N. *Tectonophysics,* **59,** 217–31.

BROOK, M., BREWER, M. S. & POWELL, D. 1976. Grenville ages for rocks in the Moine of northwestern Scotland. *Nature, London,* **260,** 515–7.

BUTLER, R. W. H. 1982. A structural analysis of the Moine Thrust Zone between Loch Eriboll and Foinaven, NW Scotland. *J. struct. Geol.* **4,** 19–29.

CASSELL, B. R. 1982. Synthetic seismograms for the northern part of the laterally varying LISPB structure. *Eos. Trans. Am. geophys. Union,* **63,** 1277.

COOK, F. A., ALBAUGH, D. S., BROWN, L. D., KAUFMAN, S., OLIVER, J. E. & HATCHER, R. D. 1979. Thin-skinned tectonics in the crystalline southern Appalachians: COCORP seismic reflection profiling of the Blue Ridge and Piedmont. *Geology,* **7,** 563–7.

——, BROWN, L. D., KAUFMAN, S., OLIVER, J. E. & PETERSEN, T. A. 1981. COCORP seismic profiling of the Appalachian orogen beneath the coastal plain of Georgia. *Bull. geol. Soc. Am.* **93,** 738–48.

—— & OLIVER, J. E. 1981. The Late Precambrian–Early Palaeozoic continental edge in the Appalachian orogen. *Am. J. Sci.* **281,** 993–1008.

COWARD, M. 1980. The Caledonian thrust and shear zones of NW Scotland. *J. struct. Geol.* **2,** 11–17.

ELLIOTT, D. & JOHNSON, M. R. W. 1980. Structural evolution in the northern part of the Moine thrust belt, NW Scotland. *Trans. R. Soc. Edinburgh Earth Sci.* **71,** 69–96.

FLINN, D., FRANK, P. L., BROOK, M. & PRINGLE, I. R. 1979. Basement-cover relations in Shetland, *In:* HARRIS, A. L., HOLLAND, C. H. & LEAKE, B. E. (eds). *The Caledonides of the British Isles—Reviewed.* Spec. Publ. geol. Soc. London, **8,** 109–16.

HALL, J. 1978. 'LUST'—a seismic refraction survey of the Lewisian basement complex in NW Scotland. *J. geol. Soc. London,* **135,** 555–63.

—— & AL-HADDAD, F. M. 1976. Seismic velocities in the Lewisian metamorphic complex, northwest Britain—'in situ' measurements. *Scott. J. Geol.* **12,** 305–14.

—— & SIMMONS, G. 1979. Seismic velocities of Lewisian metamorphic rocks at pressures to 8 kbar: relationship to crustal layering in North Britain. *Geophys. J. R. astron. Soc.* **58,** 337–47.

HARRIS, A. L. & PITCHER, W. S. 1975. The Dalradian super-group. *In:* HARRIS, A. L., SHACKLETON, R. M., WATSON, J., DOWNIE, C., HARLAND, W. B. & MOORBATH, S. (eds). *A Correlation of the Precambrian Rocks in the British Isles.* Spec. Rep. geol. Soc. London, **6,** 52–75.

HARRIS, L. D., HARRIS, A. G., DE WITT, W. & BAYER, K. C. 1981. Evaluation of the southern eastern overthrust belt beneath Blue Ridge—Piedmont Thrust. *Bull. Am. Assoc. Petrol. Geol.* **65,** 2497–505.

HUTTON, V. R. S., INGHAM, M. R. & MBIPOM, E. W. 1980. An electrical model of the crust and upper mantle in Scotland. *Nature, London,* **287,** 30–3.

JACKSON, J. A., FITCH, T. J. & MCKENZIE, D. P. 1981. Active thrusting and the evolution of the Zagros fold belt. *In:* MCCLAY, K. R. & PRICE, N. J. (eds). *Thrust and Nappe Tectonics.* Spec. Publ. geol. Soc. London, **9,** 371–9.

JACOB, A. W. B. & BOOTH, D. C. 1977. Observations of PS reflections from the Moho. *J. Geophys.* **43,** 687–92.

JOHNSTONE, G. S. 1975. The Moine Succession. *In:* HARRIS, A. L., SHACKLETON, R. M., WATSON, J., HARLAND, W. B. & MOORBATH, S. (eds.). *A Correlation of Precambrian Rocks in the British Isles.* Spec. Rep. geol. Soc. London, **6,** 30–42.

JONES, E. J. W. 1981. Seismic refraction shooting on the continental margin west of the Outer Hebrides, northwest Scotland. *J. geophys. Res.* **86,** 11553–74.

LONG, L. T. 1979. The Carolina slate belt—evidence of a continental rift zone. *Geology,* **7,** 180–4.

MENDUM, J. R. 1979. Caledonian thrusting in NW Scotland. *In:* HARRIS, A. L., HOLLAND, C. H. & LEAKE, B. E. (eds). *Caledonides of the British Isles—Reviewed.* Spec. Publ. geol. Soc. London, **8,** 291–8.

PEACH, B. N., HORNE, J., GUNN, W., CLOUGH, C. T., HINXMAN, L. & TEALL, J. J. H., 1907. *The geological structure of the northwest Highlands of Scotland.* Mem. geol. Surv. U.K.

RATCLIFFE, N. M. & HARWOOD, D. S. 1975. Blastomylonites associated with recumbent folds and overthrusts at the western edge of the Berkshire massif, Connecticut and Massachusetts—a preliminary report. *Prof. Pap. U.S. geol. Surv.* **888A,** 1–19.

—— & HATCH, N. L. 1979. A traverse across the Taconide zone in the area of the Berkshire Massif, western Massachusetts. *In:* SKEHAN, J. W., OSBERG, S. J. & OSBERG, P. H. (eds). *The Caledonides in the U.S.A.: Contributions to the International Geological Correlation Program—Project 27,* Weston Observatory, Boston College, Weston, Ma 02193, 175–200.

RODGERS, J. 1968. The eastern-edge of the North American continent during the Cambrian and Early Ordovician.

In: ZEN, E-AN, WHITE, W., HADLEY, J. B. & THOMPSON, J. B. *Studies of Appalachian Geology: Northern and Maritime.* Wiley, New York, 141–50.

SIBSON, R. H. 1977. Fault rocks and fault mechanisms. *J. geol. Soc. London,* **133,** 191–213.

SMITH, P. J. & BOTT, M. H. P. 1975. Structure of the crust beneath the Caledonian foreland and Caledonian belt of the north Scottish Shelf region. *Geophys. J. R. astron. Soc.* **40,** 187–205.

SMITH, R. L., STEARN, J. E. F. & PIPER, J. D. A. 1983. Palaeomagnetic studies of the Torridonian sediments, NW Scotland. *Scott. J. Geol.* **19,** 29–45.

SMYTHE, D. K. 1980. The deep structure of the Moine and Outer Isles Thrusts north of Cape Wrath and Lewis. *Geophys. J. R. astron. Soc.* **61,** 199.

SMYTHE, D. K. 1982. Results of the Moine Outer Isles Seismic Traverse (MOIST) (abs.) *Newsl. geol. Soc. London,* **11,** 11.

——, DOBINSON, A., MCQUILLIN, R., BREWER, J. A., MATTHEWS, D. H., BLUNDELL, D. J. & KELK, B. 1982. Deep structure of the Scottish Caledonides revealed by the MOIST reflection profile. *Nature, London,* **299,** 338–40.

SOPER, N. J. & BARBER, A. J. 1982. A model for the deep structure of the Moine Thrust Zone. *J. geol. Soc. London,* **139,** 127–38.

SWETT, K. & SMIT, D. E. 1972. Paleogeography and depositional environments of the Cambro-Ordovician shallow marine facies of the North Atlantic. *Bull. geol. Soc. Am.* **83,** 3223–48.

THOMPSON, B. G. 1982. *Crustal electrical conductivity studies in the Georgia Piedmont.* Thesis, PhD, Cornell Univ. (unpubl.).

WATERS, K. H. 1981. *Reflection Seismology* (2nd edition). Wylie, New York, 453 pp.

WATSON, J. 1976. The Lewisian Complex. *In:* HARRIS, A. L., SHACKLETON, R. M., WATSON, J., HARLAND, W. B. & MOORBATH, S. (eds). *A Correlation of Precambrian Rocks in the British Isles.* Spec. Rep. geol. Soc. London, **6,** 15–29.

WATSON, J. & DUNNING, F. W. 1979. Basement-cover relations in the British Caledonides. *In:* HARRIS, A. L., HOLLAND, C. H. & LEAKE, B. E. (eds). *Caledonides of the British Isles—Reviewed.* Spec. Publ. geol. Soc. London, **8,** 67–92.

WESTBROOK, G. K. & BORRADAILE, G. J. 1978. The geological significance of magnetic anomalies in the region of Islay. *Scott. J. Geol.* **14,** 213–24.

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