Table 2 Comparisons of basalt compositions

Tempera-ture (°C)§	9 kbar‡ melts (present study)							MORB[17]		Second-stage melts[2]			Plag-rich vein[16]
	1,210	1,225	1,250	1,275	1,300	1,325	1,350	B_1	B_2	(3)	(4)	(11)	9W21
SiO_2	50.61 (0.7)‖	51.64 (0.8)	51.44 (0.7)	51.65 (0.8)	51.18 (0.8)	51.34 (0.6)	51.12 (0.4)	48.53	51.20	54.20	52.40	53.30	49.31
TiO_2	0.36 (0.06)	0.34 (0.08)	0.31 (0.06)	0.34 (0.08)	0.24 (0.07)	0.20 (0.07)	0.19 (0.04)	0.62	0.87	0.40	0.30	0.60	0.12
Al_2O_3	17.73 (0.8)	15.53 (0.5)	15.08 (0.5)	15.06 (0.7)	13.98 (0.7)	13.50 (0.6)	11.25 (0.8)	16.65	15.03	15.40	11.70	14.40	15.59
FeO*	7.14 (0.3)	7.84 (0.5)	7.23 (0.4)	7.50 (0.5)	8.69 (0.4)	9.30 (0.6)	9.44 (0.8)	8.41	8.39	7.90	8.40	9.90	8.09
MgO	8.52 (0.5)	10.6 (0.3)	11.63 (0.7)	12.03 (0.6)	14.38 (0.4)	15.39 (0.5)	15.91 (0.4)	10.25	9.21	8.70	15.80	7.80	12.78
CaO	13.26 (0.6)	13.51 (0.4)	12.87 (0.8)	13.29 (0.4)	11.12 (0.5)	10.03 (0.5)	10.10 (0.6)	12.68	12.73	11.50	10.70	12.40	13.30
Na_2O	0.48 (0.09)	0.48 (0.05)	0.48 (0.04)	0.44 (0.04)	0.41 (0.05)	0.33 (0.07)	0.21 (0.03)	2.26	1.87	1.60	0.70	1.70	0.52
K_2O	0.10 (0.04)	0.07 (0.04)	0.09 (0.03)	0.05 (0.03)	0.05 (0.03)	0.07 (0.04)	0.07 (0.04)	0.06	0.10	0.10	0.10	0.10	0.02
Cr_2O_3	0.03 (0.01)	0.03 (0.01)	0.02 (0.01)	0.29 (0.04)	0.36 (0.04)	0.47 (0.03)	0.48 (0.04)	0.03	0.07	n.d.	n.d.	n.d.	
CIPW norm													
q	4.92	3.28	3.11	2.28	0.36	0.14	0.97	—	—	5.47	—	3.59	—
or	0.60	0.41	0.54	0.29	0.29	0.41	1.42	0.25	0.57	0.59	0.59	0.59	0.12
ab	4.14	4.06	4.10	3.71	3.49	2.79	1.81	17.71	15.80	13.57	5.92	14.36	4.31
an	46.32	39.99	39.11	38.50	36.10	35.09	29.74	35.84	32.31	34.61	28.45	31.30	49.30
di	8.23	10.94	10.59	10.95	7.82	5.88	8.74	22.10	25.20	9.20	9.88	12.40	10.46
hy	26.54	29.73	29.25	32.41	43.96	49.32	49.34	—	21.65	26.61	44.65	24.31	27.66
ol	—	—	—	—	—	—	—	21.64	2.36	—	0.065	—	6.40
il	0.50	0.64	0.59	0.64	0.46	0.38	0.37	1.02	1.60	0.76	0.57	1.14	0.22
[Mg/(Mg+Fe)]*	0.887	0.902	0.903	0.909	0.910	0.914	0.916						
[Mg/(Mg+Fe)]†	0.876	0.889	0.905	0.905	0.908	0.909	0.910						

* [Mg/(Mg+Fe)] ratio in olivine analysed with the electron microprobe.

† [Mg/(Mg+Fe)] ratio in equilibrium olivine calculated on the basis of $K_D = (Fe/Mg)^{olivine}/(Fe/Mg)^{melt} = 0.3$ (ref. 23).

‡ An uncertainty of ±0.5 kbar exists.

§ The nominal temperature values quoted are good within ±10 °C.

‖ Standard deviation given in parentheses.

melts is remarkable. Such compositional resemblance possibly suggests that at least some MORBs (second-stage melts) are primary and that they may be generated at shallow depths (~30 km).

A final comparison can be made with a proposed primary magma from the Trinity mafic–ultramafic complex[16]. These 'melts'[16] occur as plagioclase-rich veins in host plagioclase lherzolite. Using compositional, field and phase equilibria arguments, Quick suggested that these melts were generated at pressures of <10 kbar. Table 2 shows that these veins are compositionally similar, including Na_2O contents, to some of the experimental melts, which supports the conclusion of Quick. It is further suggested that the source lherzolite for such melts must have undergone previous partial fusion and depletion in elements such as Na.

Application of the results of this experimental study to the MORBs and possible primary melts of the Trinity complex therefore supports the contention that the high-MgO, high-SiO_2 basalts of the mid-ocean ridges are primary, and are generated at relatively shallow mantle depths, possibly from plagioclase + spinel lherzolite.

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Deep structure of the Scottish Caledonides revealed by the MOIST reflection profile

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The Moine and Outer Isles Seismic Traverse (MOIST) is a deep crustal reflection profile shot at sea off the north coast of Scotland in 1981. Spectacular reflections are observed from the Moho and from thrust zones within the Caledonian fold belt and foreland. Deep reflection profiling of the continental crust of the United States under the direction of the COCORP group, has amply demonstrated the value of this technique when applied to suitable geological problems (see, for example, refs 1, 2). A similar group, the British Institutes Reflection Profiling Syndicate (BIRPS), has now been set up in the UK to organize such projects. Funds are provided by the Natural Environment Research Council (NERC) through the core group based at Cambridge University. However, a preliminary experiment, of which MOIST is the result, was organized through the Institute of Geological Sciences (IGS).

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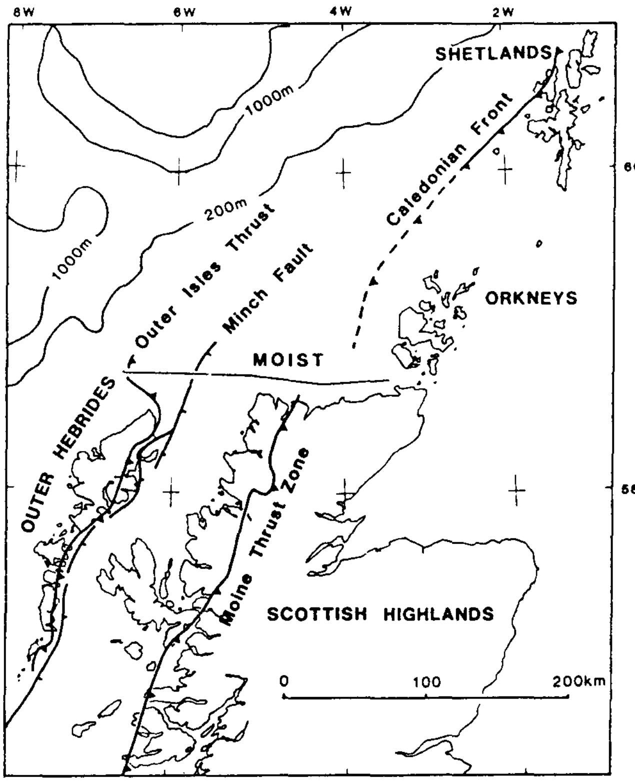

Fig. 1 Location of MOIST in relation to the Caledonian orogenic front off northern Scotland.

The strategy of recording reflection profiles offshore was adopted because a number of areas of basement outcrop around the United Kingdom are known to give rise to good upper- and mid-crustal reflections on confidential commercial reflection data[3-5]. Furthermore, shooting at sea is nearly an order of magnitude cheaper, mile for mile, than on land, as well as giving better quality data, although the obvious drawback is that reflections cannot be tied in directly to exposed outcrop.

One of the most important targets for reflection profiling in the UK is the Caledonian orogenic front (Fig. 1), which runs the length of north-west Scotland, trending north-east offshore from the Scottish mainland towards the Shetlands[6]. The nature of the front and the deeper crustal structure of the Moine Thrust zone and Outer Isles Thrust are the subject of several conflicting hypotheses, referred to below. There is a good coverage of industry reflection data offshore, recorded mainly to 5 s two-way time (TWT)—up to 15 km of crustal penetration—and several major crustal refraction profiles have been observed both offshore and onshore[7-10]. Although in many respects these long refraction profiles have proved disappointing in their lack of resolution of crustal problems, they do at least define well the Moho depth, which is about 25 km below the foreland.

MOIST crosses the offshore extrapolation of the Caledonian fold belt and runs onto the foreland to the west (Fig. 1). Its precise location was fixed with the help of the commercial data[3], avoiding as far as possible the complicating effects of plutons and other intrusions. The survey comprised one line running from the Pentland Firth to 30 km NW of the Butt of Lewis, a total of 181 km (Fig. 1). The line consisted of three straight segments run close to and parallel to the coast for best possible correlation with known land geology, but sufficiently far offshore to minimize side swipe interference from charted coastal features.

The survey was conducted by Western Geophysical Company of America, using essentially the same equipment as for conventional oil industry surveys, except that the source and detector were towed at a greater depth to optimize the lower frequency signal content. The source was a 905 in^3 tuned airgun array operating at 4,500 p.s.i. pressure, towed at a depth of 12 m. The 3-km hydrophone streamer, comprising 60 × 50 m sections, was towed at a depth of 15 m. Shot interval was 50 m. Sixty channels were recorded at a 4-ms sampling rate to a record length of 15 s. Positioning was by satellite navigator integrated with bottom tracking Doppler sonar.

A conventional basic processing sequence was followed to produce final stacked sections with 30-fold subsurface coverage at a 25-m common depth point interval. In addition, array simulation techniques were used before stacking, to enhance the continuity of events deep in the section. The operator lengths were equivalent to a 200-m source array and a 100-m

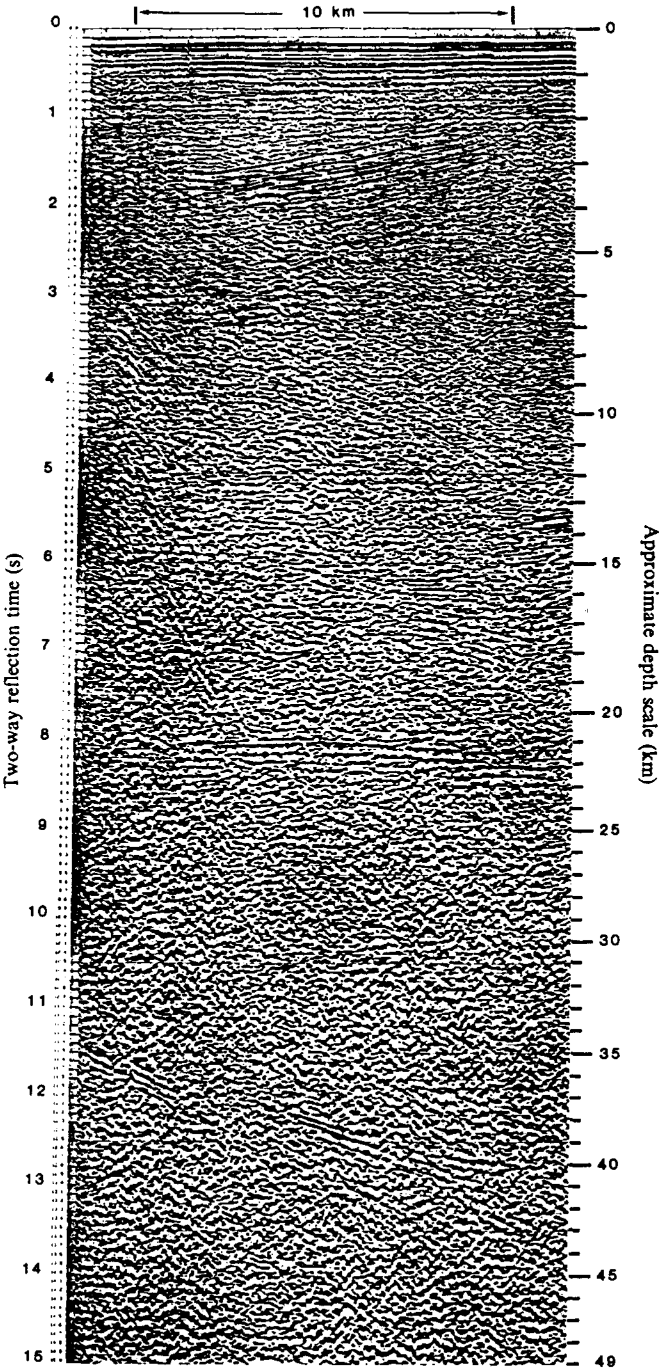

Fig. 2 Part of the final equalized stack section processed by Western Geophysical (located in Fig. 3). Strong reflectors at 1.4–1.8 s TWT are from Permo-Triassic redbeds below Jurassic shales. The Moho is at 8.0 s TWT and the 'Flannan Thrust' reflectors dip east between 12 and 13 s TWT. Depth scale on right is approximate.

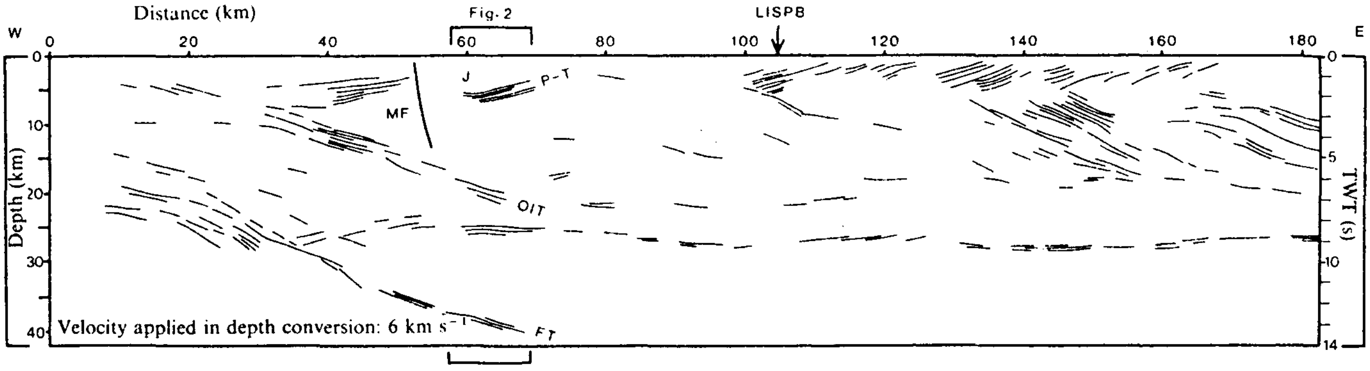

Fig. 3 Line drawing of MOIST profile, based on migrated sections but also using data from unmigrated stacks. Vertical depth scale assumes a constant velocity of 6 km s^{-1}; no vertical exaggeration. LISPB intersection near Cape Wrath is shown. MF, Minch Fault (drawn from other data); J, Jurassic; P–T, Permo-Triassic; OIT, Outer Isles Thrust; FT, Flannan Thrust.

receiver array. Velocity analyses were computed at 3-km intervals.

Figure 2 shows part of the equalized stack section resulting from the above processes, showing the excellent data quality. Figure 3 is a line drawing based on a migrated section produced for BIRPS by Shell Expro UK Ltd, but also using the information from the conventional stack (for example, Fig. 2) together with other migrations subsequently produced by one of us (J.A.B.) on the COCORP computer at Cornell University.

The base of the crust is well defined by an almost continuous Moho reflector along most of the section, 35–181 km, at a depth of around 25 km, in good agreement with the LISPB and NASP profiles[7,8]. Apparent vertical offsets in TWT, for example, astride the Minch fault, may be due to structural offsets in the Moho, although pull-up effects due to lateral variations in crustal P-wave velocity cannot be ruled out. The W-dipping reflectors in the uppermost 2–3 s TWT are from sediments in half-grabens of ages ranging from Proterozoic (?Stoer Group, 990 Myr) to Jurassic. Lewisian basement of Laxfordian (~1,700 Myr) or older age, forming the sub-sedimentary crop along the westernmost two-thirds of the profile, is the apparently autochthonous foreland. It generally lacks coherent reflectors, but in the western half of the profile is cut by two sequences of reflectors dipping east at around 20°. The upper of these corresponds to the northward offshore extension[3] of the Outer Isles Thrust, a major intra-foreland thrust zone cropping out along the eastern coastline of the Outer Hebrides. The thrust appears either to flatten out at ~20 km depth or to cut and displace the Moho (Fig. 3, 70–90 km along profile). In either case, it has clearly been reactivated as a low-angle normal fault, permitting deposition of the westward dipping sediments above. Comparisons with the geologically better controlled geophysical data in the Minches and Sea of the Hebrides[11–14] suggest that the Stoer Group (~990 Myr) and/or Torridon Group (~810 Myr) piedmont fan and fluvial deposits[15–17] may form the base of these sedimentary prisms, in which case the Outer Isles Thrust would be of Grenville or earlier age.

The deeper sequence of eastward-dipping reflectors was totally unexpected. It appears to truncate the Moho (Fig. 3, 35 km along profile) and can be traced convincingly to 13 s TWT (Figs 2, 3)—about 40 km depth. The reflectors are primary, not multiple, events; their apparent termination of the Moho, and their parallelism with the overlying Outer Isles Thrust, suggest that the reflector group lies approximately in the plane of section, and that it is due to another thrust. We call it the Flannan Thrust, since it may crop out along the western margin of the Flannan Trough[18–20] west of the Hebrides.

The west-dipping half-grabens seen along the eastern part of the section (Fig. 3, 100–170 km along profile) contain red beds of late Palaeozoic age. The easterly-downthrowing faults bounding the sedimentary prisms presumably flatten out into the group of prominent east-dipping reflectors beneath, which have been interpreted[3] as due to intra-orogenic belt structure. Our new interpretation of these requires a fuller discussion (J.A.B. and D.K.S., in preparation) than can be given here; however, the data suggest that thrust structures flatten out at 17–20 km depth. Thus, thin-skinned models[21–23] of the Moine Thrust Zone and 'duplex' models of full crustal thickness[24] appear to be incorrect.

In conclusion, MOIST demonstrates that conventional marine seismic reflection techniques are indeed now capable of profiling the whole continental crust, contrary to pessimistic theoretical predictions[25], and also, that reflection profiling, even when located offshore, can be an extremely powerful tool for testing *a priori* hypotheses. We stress, however, that line drawings such as that in Fig. 3 cannot simply be 'coloured in' with a geological interpretation; new and better-constrained hypotheses can only emerge from a synthesis of all available geological and geophysical data.

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