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BIRPS deep seismic reflection studies of the British Caledonides

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The Western Isles–North Channel (WINCH) traverse (Fig. 1), an extension of the successful MOIST profile[1], was recorded in 1982 at sea along the west coast of Britain for BIRPS (British Institutions Reflection Profiling Syndicate) by the Geophysical Company of Norway (GECO). The purpose of the WINCH traverse was to study crustal structure of the Caledonian foreland, to cross the Caledonian orogen, and to establish the three-dimensional geometry of mantle reflectors originally seen on MOIST. We describe here the data, first emphasizing British Caledonian structures, and then discussing features of the deep crust of wider significance. The data are of very good quality and contain clear Moho and upper mantle reflections. The lower crust is surprisingly reflective, deeply penetrative thrusts are observed and there is firm evidence that several of the Mesozoic basins round the shores of the United Kingdom were formed by reactivation of older features.

An extended airgun array (180 m long) towed at 8 m depth was used for the measurements, with a total volume of 4,795 in^2, operated at a pressure of about 2,000 p.s.i. which delivered ~120 bar metres. Data were recorded to 15 s with a 60-channel streamer ~3 km long towed at 15 m depth. GECO also processed the data using conventional industrial procedures. Receiver array simulation together with the extended source had the effect of enhancing deep reflections, although at some expense to the resolution of shallow (<1–2 s) events. The data, stacked at 30-fold, are available at cost of reproduction from the Institute of Geological Sciences in Edinburgh.

Line drawings of WINCH are shown in Fig. 2 and an example of the data is shown in Fig. 3. A striking feature of the profile is that, unlike the lower crust, the upper crust over much of the line is seismically transparent. Of the major geological boundaries mapped onshore in Britain, the southerly extension of the Moine Thrust (Loch Skerrols Thrust), the Highland Boundary Fault and the Southern Uplands Fault cannot be seen. This implies that, at the scale of the wavelengths of the WINCH data (150–800 m), either these boundaries do not have a sufficient impedance contrast (change in velocity–density product), or that the boundaries are too steep to be properly imaged and there is no contrast in seismic character across them. This further implies either that at depth the geological features are insignificant or that they have died out offshore where crossed by WINCH.

The important structures of the Caledonides seen on WINCH are the Outer Isles Thrust, the Great Glen Fault Zone, the Iapetus Suture, and the South Irish Sea Lineament. The Great Glen Fault Zone (for which 2,000 km of lateral motion has been claimed[3]) is probably a vertical feature in the near surface consisting of at least two fault splays[2] inferred from reflected refractions. At depth the Great Glen Fault may extend vertically into the mantle because pronounced southerly dipping reflectors lying south of the fault zone between 10 and 13 s (~30–40 km depth) appear to be truncated (Fig. 2). Oblique reflections and offline diffractions, which are very strong in this area, complicate this interpretation and have not been removed successfully at the present stage of processing.

The Iapetus Suture (marking the position of final closure

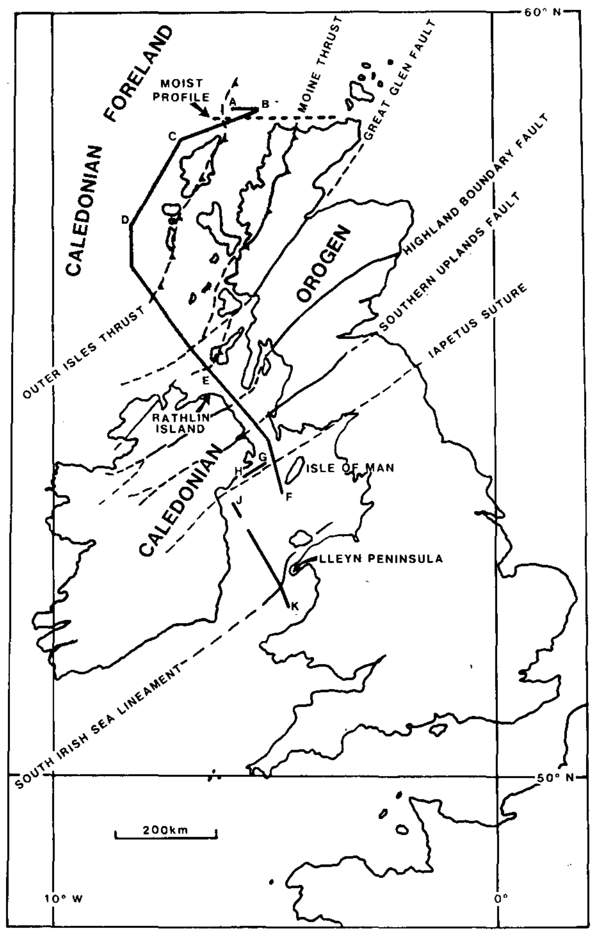

Fig. 1 Location of WINCH with respect to Caledonian foreland and orogen, and major Caledonian faults. Letters alongside profile refer to line drawing segments in Fig. 2.

between the Baltic and North American plates towards the end of Caledonian events[4]) is not apparent in the top 3 s (uppermost 10 km). However, a pronounced change in crustal reflection character occurs between ~10 km depth and the Moho depth at 30 km, and the suture may be defined here by the north-dipping top surface of the very reflective lower crustal wedge. To the north, under the Midland Valley, few reflectors are seen but to the south the middle and lower crust of northern England contains numerous reflecting horizons.

The Outer Isles Thrust[5] and the South Irish Sea Lineament are the only features on WINCH which can be traced as continuous reflecting zones from the surface into the lower crust. The Outer Isles Thrust (seen on two of the WINCH lines and on MOIST) dips east at 25+/−5° to depths of 18–20 km. The South Irish Sea Lineament, which outcrops to the south-west of the Lleyn Peninsula, dips WNW at 25+/−5° to 15–18 km depth (using information provided by Shell Expro UK) and thus has an approximately Caledonoid trend. It is probably a thrust. We prefer to call this major basement feature the South Irish Sea Lineament rather than the more specific Menai Straits Line[6,7] because at present we do not know exactly which onshore structure the lineament corresponds to.

Sedimentary basins are clearly imaged by WINCH when they are filled with Permo-Triassic or later rocks. They have a distinctly variable character. Some are half-grabens (for example, the Minch, Colonsay and Kish Bank Basins); others are synclinal with modest dips on the limbs (for example, 10–15° for the Stanton Trough) or steep dips (for example, up to 20° for the Cardigan Bay Basin). The North Lewis Basin and the northern end of the St Georges Channel Basin are half-grabens that lie in the hanging walls of thrusts (the Outer Isles Thrust and South

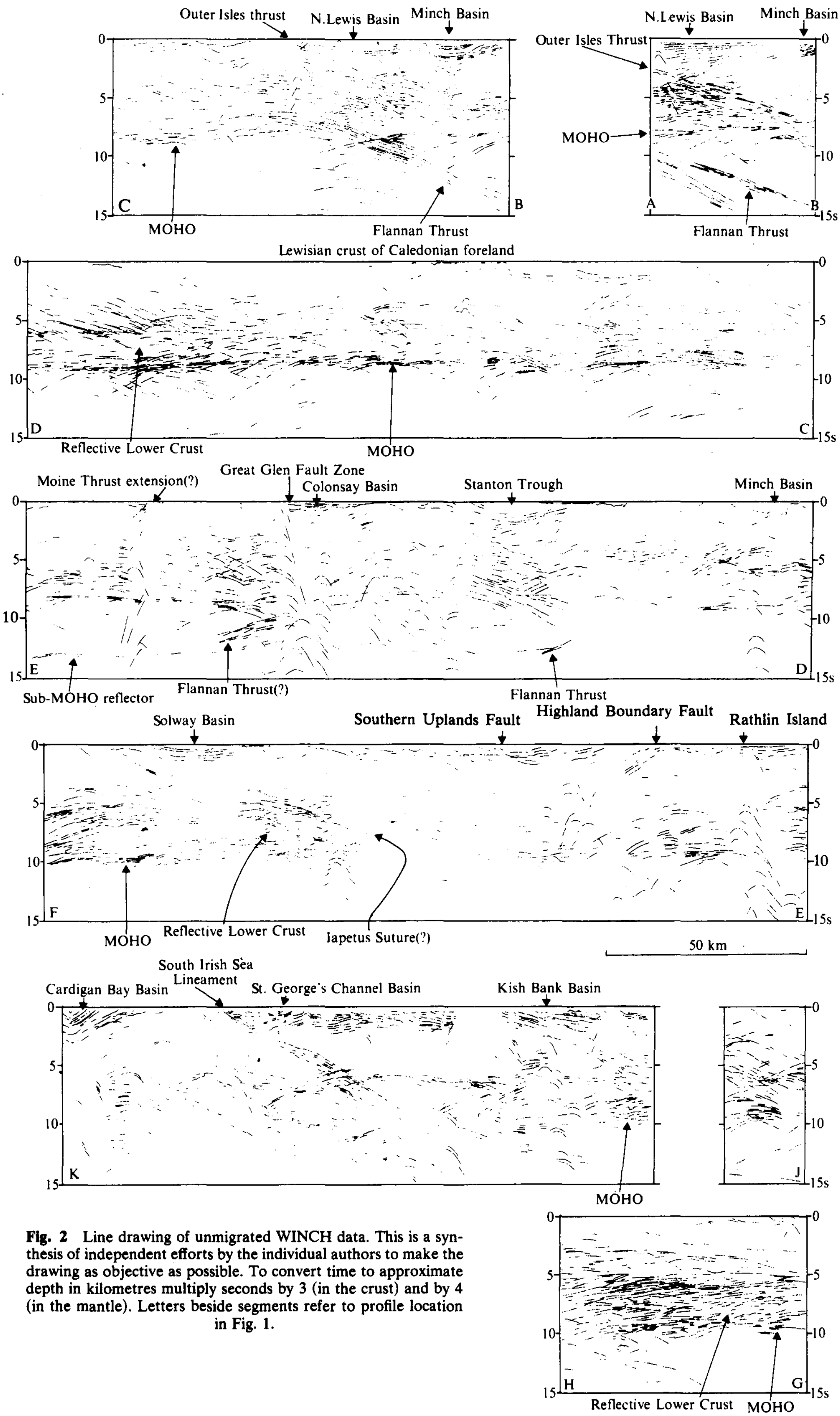

Fig. 2 Line drawing of unmigrated WINCH data. This is a synthesis of independent efforts by the individual authors to make the drawing as objective as possible. To convert time to approximate depth in kilometres multiply seconds by 3 (in the crust) and by 4 (in the mantle). Letters beside segments refer to profile location in Fig. 1.

Irish Sea Lineament respectively) and were clearly formed by the reactivation of earlier compressional features. There are other examples on the MOIST profile[1]. The Solway Basin, although synclinal, also lies above the hanging-wall of the Iapetus Suture.

WINCH provides important new information on the structure and behaviour of continental crust in general. The following conclusions can be drawn from initial inspection of the data.

(1) Extensional features—several Mesozoic basins—were formed by reactivation of earlier Caledonian basement thrusts. A striking example is shown in Fig. 3. Thrusts are rejuvenated by simple normal movements on their hanging walls (such as the Minch and North Lewis Basins). A more elaborate form of rejuvenation, the 'domino' effect in which normal faults are formed by tilting and rotation of a series of subparallel earlier thrusts, is seen on MOIST along the offshore extension of the Moine Thrust Zone. Basins that formed by simple normal movements along earlier thrusts are also seen on COCORP data crossing the Coastal Plain of the eastern USA[8]. These observations complement inferences that currently active thrusts reactivate earlier normal faults along the Zagros Fold Belt[9].

Because these basement thrusts are important to the structure and evolution of the sedimentary basins, study of the basement clearly is commercially advantageous. Mapping of basement reflectors could be carried out by the oil industry with minimal extra effort and expense if commercial seismic data were recorded to 7–10 s as a matter of course[10].

(2) Acoustic boundaries on WINCH cannot be traced with certainty from the surface to the Moho or vice versa. The Outer Isles Thrust and South Irish Sea Lineament are well defined reflecting horizons in the upper crust which, however, seem to die out in the lower crust. These horizons therefore seem to be comparable with thrusts seen on COCORP data, such as the Wind River Thrust in Wyoming[11] and possibly the Mountain View Fault in Oklahoma[12], which also cannot be traced to the Moho. The Iapetus Suture is an example of a marked contrast of reflection character in the lower crust which cannot with confidence be traced to the surface, and the Great Glen Fault can be seen possibly in the lower crust and upper mantle as a vertical zone of reflector truncations but is poorly defined in the upper crust.

(3) The lower and middle crust has a very pronounced reflection character over much of WINCH, while the upper crust is often remarkably transparent. Antiformal reflections and diffractions that criss-cross in a complex manner in the lower crust will need careful migration to be properly resolved. With the exception of the suggested trace of the Iapetus Suture, there is little obvious correlation between variations in this lower crustal reflecting zone and changes in surface geology. Similarly reflective lower crust has been described from parts of Europe (R. Meissner, personal communication), Australia[13] and on COCORP data in the United States[14].

(4) Moho character is highly variable. Strong and fairly continuous Moho reflections are seen under the Caledonian Foreland where crystalline basement is close to the surface and Moho depth is relatively constant at 26–30 km. This character is consistent with that inferred from wide-angle reflection and refraction experiments in this area[15,16]. Under the orogen the Moho reflection is much more discontinuous, possibly due to the complexities of geology and wave paths in the near-surface. Sometimes the Moho appears to be simply the base of the lower crustal reflecting zone (for example, in the region of the Irish Sea just south of the Iapetus Suture). Further south, under the central and southern Irish Sea, the Moho is difficult to identify. Perhaps this is related to the presence of an anomalous 7.3 km s^{-1} lower crustal layer determined by refraction experiments[17]. Such clear and relatively continuous Moho reflectors as are observed in the Caledonian Foreland have not yet been reported elsewhere.

(5) Strong and continuous reflectors from the mantle, which to our knowledge have also not yet been recorded elsewhere, occur on the portion of WINCH north of Rathlin Island (Figs 1, 2).

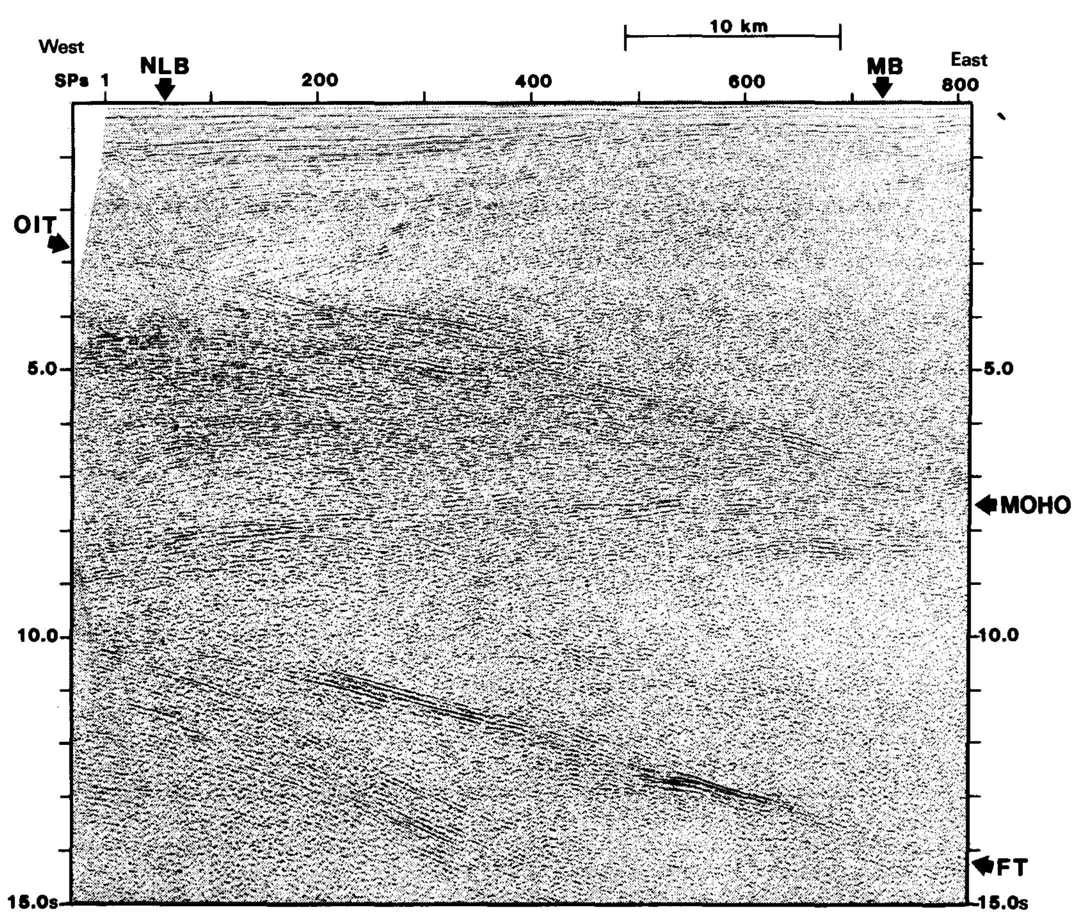

Fig. 3 WINCH unmigrated profile A–B (Fig. 1). NLB, North Lewis Basin; MB, Minch Basin; OIT, Outer Isles Thrust; FT, Flannan Thrust.

The most spectacular of these, the Flannan Thrust, lies north of the Hebrides and is seen on two WINCH lines and on MOIST[1]. The seismic data show that it dips at 25–35° ENE, subparallel to the Outer Isles Thrust. The Flannan Thrust is the only reflector on WINCH which unequivocally cuts the Moho, above which it flattens in the lower and middle crust. We suspect that it may not continue to the surface. We therefore do not know the nature of this feature but suspect it is a Caledonian thrust because it has a similar attitude to the Outer Isles and Moine Thrusts.

The Flannan Thrust probably extends south of the Hebrides because a fairly weak reflector in the mantle occurs in the expected position along strike. We speculate that the Flannan Thrust is also the cause of the zone of south-dipping reflectors lying between 10 and 13 s south of the Great Glen Fault Zone (Fig. 2). If so, and if these reflectors are indeed truncated north of the fault zone, they would imply ~100–150 km of left-lateral offset along the Great Glen. A sub-horizontal mantle reflection at 35–40 km depth underlies the possible continuation of the Flannan Thrust south of the Hebrides and south of the Great Glen and may be a detachment surface into which the thrust flattens. Thus discernible seismic impedance contrasts definitely exist below the base of the Earth's crust. Clearly, 30–50 s reflection data are required to study upper mantle structures and determine the deeper extent of the Flannan Thrust.

The WINCH data are the second phase of a programme to study the deep crustal structure round the United Kingdom by seismic profiling. Detailed descriptions and analyses are in preparation. However, the data contain fascinating new information about the nature of continental crust and upper mantle. Much of the deep structure of the Caledonian orogen is resolvable and the presence of such features as the Flannan Thrust and the highly reflective lower crust need to be explained in any model of the formation of the orogen.

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