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Reflection seismic evidence for a Moho offset beneath the Walls Boundary strike-slip fault

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Abstract: BIRPS has acquired two deep seismic reflection profiles across the Walls Boundary Fault, a major late Caledonian strike-slip fault that is probably the northern continuation of the Great Glen Fault of Scotland. Where crossed by the SHET deep seismic survey north of the Shetlands, the Walls Boundary Fault appears to be a narrow vertical structure which penetrates the entire crustal thickness and juxtaposes crusts of different thicknesses. The seismic data show a Moho offset in travel-time of 1.0–1.5 seconds and two high-amplitude diffractions originating at Moho travel-times. These diffractions are, as yet, unique among seismic data across strike-slip faults and can be used to argue that the Moho is offset in depth by 2–3 km over a lateral distance of less than 6 km. Seismic modelling is used to constrain this interpretation. The preservation of this Moho topography suggests that the structure and rheology of the lower crust of the Shetland Platform was not significantly modified during post-Devonian extension of the North Sea and Atlantic margin.

Deep seismic reflection profiling is increasingly being used to study the nature and geometry at depth of structures mapped at the surface. Of particular interest are the major strike-slip faults found on the continents. Several of these have been recognized to be the transform boundaries between major plates (the San Andreas, Alpine, and Queen Charlotte faults for example), while others accommodate stresses within the boundaries of the continents (the Great Glen, North Anatolian, and Garlock faults). The surface expression of these structures is usually well-defined, either as a single fault zone or as a set of parallel or anastomosing faults of measurable width and offset. However, neither the deeper geometry of these structures nor the way in which the displacement observed at the surface is accommodated at depth within the lithosphere is well understood (Sibson 1983).

In August 1984, the British Institutions Reflection Profiling Syndicate (BIRPS) collected 830 km of deep multichannel seismic reflection data (the SHET survey) on the continental shelf surrounding the Shetlands, north of Scotland (Fig. 1). One of the major goals of the SHET survey was to study the deep structure of the Walls Boundary Fault (WBF), a major strike-slip fault in the Shetlands thought to be the northern continuation of the Great Glen Fault system in Scotland (Flinn 1961). Two of the SHET profiles cross the offshore continuation of the WBF: UNST north of the Shetlands and FAIR ISLE south of the Shetlands (Fig. 1).

This paper presents the interesting and somewhat surprising features of these two profiles across the WBF and shows the results of forward seismic modelling used to constrain their interpretation. In particular, this paper investigates the geometry of the WBF at Moho depths and the bearing of these results on the nature of strike-slip faults at depth and the rheology of the lower crust.

The Walls Boundary Fault

The Walls Boundary Fault is the most important structural discontinuity in the Shetlands (Flinn 1961; Mykura 1976). It is exposed as a zone of intensely fractured rock, including slices of mylonite, which is usually fairly narrow but can be up to a kilometre in width (Flinn 1977). The fault can be clearly traced on the continental shelf as far south as Fair Isle (Fig. 1) and is the likely northern continuation of the transcurrent Great Glen Fault in Scotland (Flinn 1961, 1969; McQuillin *et al.* 1982).

The Great Glen Fault is the most conspicuous member of a set of NE-SW trending wrench faults probably formed in the early Devonian during oblique continental collision in the final stages of the Caledonian orogeny (Watson 1984; Soper & Hutton 1984; Phillips 1976). The ages, directions and amounts of movement on the fault are highly controversial. Palaeomagnetic data have led investigators to argue for large sinistral displacements ranging from 600 km in the late Middle Devonian (Storetvedt 1986) to 2000 km during the Carboniferous (Van der Voo & Scotese 1981). Geological data, on the other hand, suggest an initial sinistral displacement of only about 100–200 km before the end of the Devonian (Smith & Watson 1983), followed by a post-Devonian dextral displacement of about 30 km (Donovan *et al.* 1976).

As the northern continuation of the Great Glen Fault, the Walls Boundary Fault is also likely to have experienced several episodes of transcurrent motion both during and since the end of the Caledonian orogeny. Early transcurrent motion of the WBF is not directly constrained by Shetland basement geology since the Caledonian metamorphic rocks on either side of the fault cannot be correlated, but the relative position of the Caledonian front with respect to the Dalradian and Moine equivalents on Shetland suggests 100–200 km of late Caledonian sinistral offset for the WBF as well (Flinn 1985). Later dextral motion displacing both the Old Red Sandstone and granitic plutons is estimated to be from 65 km (Flinn 1969; Donovan *et al.* 1976) to about 95 km (Astin 1982).

The timing and nature of the latest movement on either the WBF or the Great Glen Fault is again controversial (Bacon & Chesher 1974; Bott & Browitt 1975; Flinn 1975; Speight & Mitchell 1979). The WBF clearly truncates

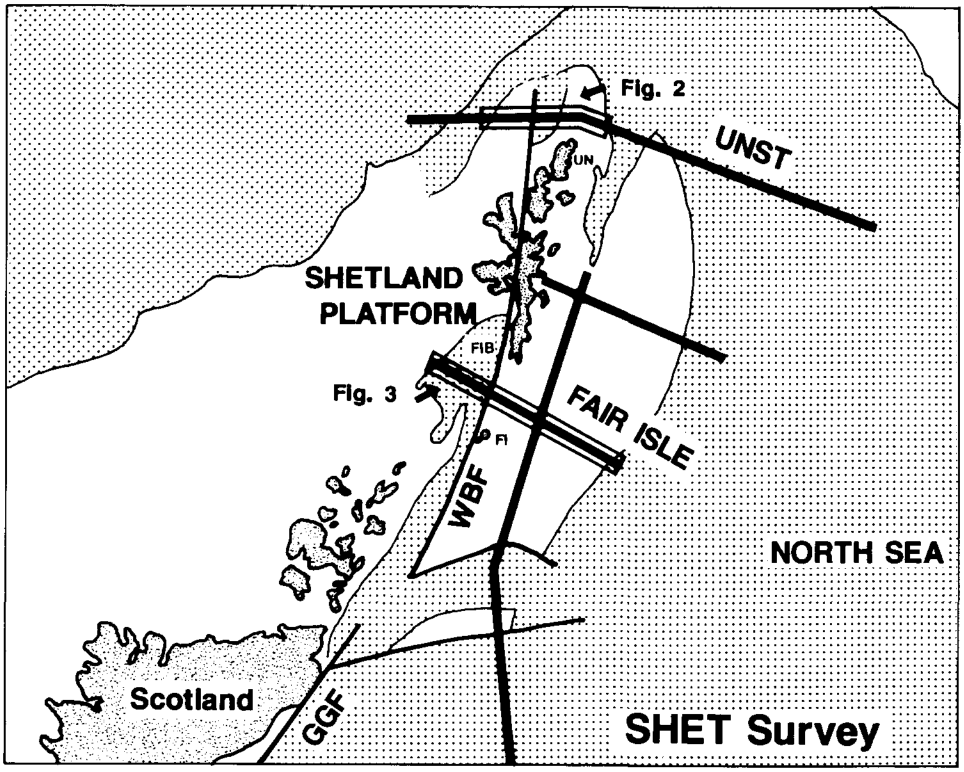

Fig. 1. Location map of the SHET deep seismic reflection survey of BIRPS. Two 15-second profiles, UNST and FAIR ISLE, cross the Walls Boundary strike-slip fault (WBF) north and south of the Shetlands. The WBF is the likely northern continuation of the Great Glen fault (GGF). Line drawing interpretations of each profile are shown in Figs 2 and 3. Land is speckled. Sedimentary basins are dotted. UN Unst island; FI, Fair Isle; FIB, Fair Isle Basin.

Permo-Triassic sedimentary rocks in the West Fair Isle Basin. Movement on the Great Glen Fault in the Moray Firth has affected sediments as young as Lower Cretaceous (McQuillin *et al.* 1982; Bacon & Chesher 1974). The latest movement is therefore post-Early Cretaceous but may have involved only minor displacement. There is no evidence in this region east and north of Scotland for any significant Tertiary displacement on the Great Glen Fault or the Walls Boundary Fault.

The BIRPS profiles; seismic interpretation

The SHET survey crosses the WBF both north and south of the Shetlands. Line drawings of the relevant parts of the two profiles, UNST and FAIR ISLE, are shown in Figs 2 and 3 respectively. Both sections were recorded to 15 seconds two-way travel-time (TWTT) allowing seismic penetration into the continental crust and mantle to a depth of about 50 km. The data are 30 fold. Below each line drawing is a geological interpretation of the seismic data. The results of the total SHET survey will be presented elsewhere (McGeary 1987).

The UNST profile

UNST crosses the WBF 35 km north of the island Unst in the Shetland Isles (Fig. 1) and extends from the Faeroe/West Shetland basin to the Viking Graben. Only the 70 km section across the WBF is shown in Fig. 2. West of the WBF, Caledonian or Archaean metamorphic basement is exposed at the sea bed, and there are few reflections within the upper crust (Fig. 2). Immediately east of the WBF, and truncated by it, is a small sedimentary basin, the Sandwick Basin, assigned to the Devonian (Hitchen & Ritchie 1987). The reflections are weak but suggest a sedimentary thickness of about 2 km. Beneath the basin and exposed at the sea bed to the east is the acoustically transparent metamorphic basement of presumed Caledonian age.

The most exciting features of the UNST profile lie at Moho depths within the section (Figs 2 and 4). West of the WBF, the Moho is interpreted to be the base of a narrow zone of high-amplitude reflections at 9.0–9.5 s TWTT (event M1 in Figs 2 and 4). Although there is no nearby refraction data to constrain this interpretation, such an interpretation has been justified in other regions by coincident refraction and wide-angle reflection data (Barton *et al.* 1984; Klemperer *et al.* 1986; Matthews 1986). Immediately east of the WBF, the Moho is not as well defined but can be seen as a discrete set of horizontal reflections at 10.7 s TWTT (event M2 in Figs 2 and 4). This abrupt change in reflection time to the Moho of about 1.5 s could be produced either by a major change in depth to the Moho across the WBF north of Shetland, a Moho offset, or by a significant difference in average crustal velocity across the fault.

The most surprising events in the profile are events D1 and D2 (Figs 2 and 4). These two events can each be seen to originate at about Moho times and to continue at opposite dips to the base of the section. The slightly curved geometry of events D1 and D2 and the fact that they each collapse to a separate finite area (a 'point') upon migration at reasonable whole crustal velocities suggest that they are both diffractions, probably from some kind of structure on the Moho. The high-amplitudes suggest that the seismic energy has been focused in some way by this structure. The apices of diffractions D1 and D2 are offset in travel-time which makes the diffractions appear asymmetric. This offset in diffraction apices may be explained in the same way as the offset on the Moho, by either Moho structure or velocity pulldown.

Both the abrupt difference in travel-time to the reflection

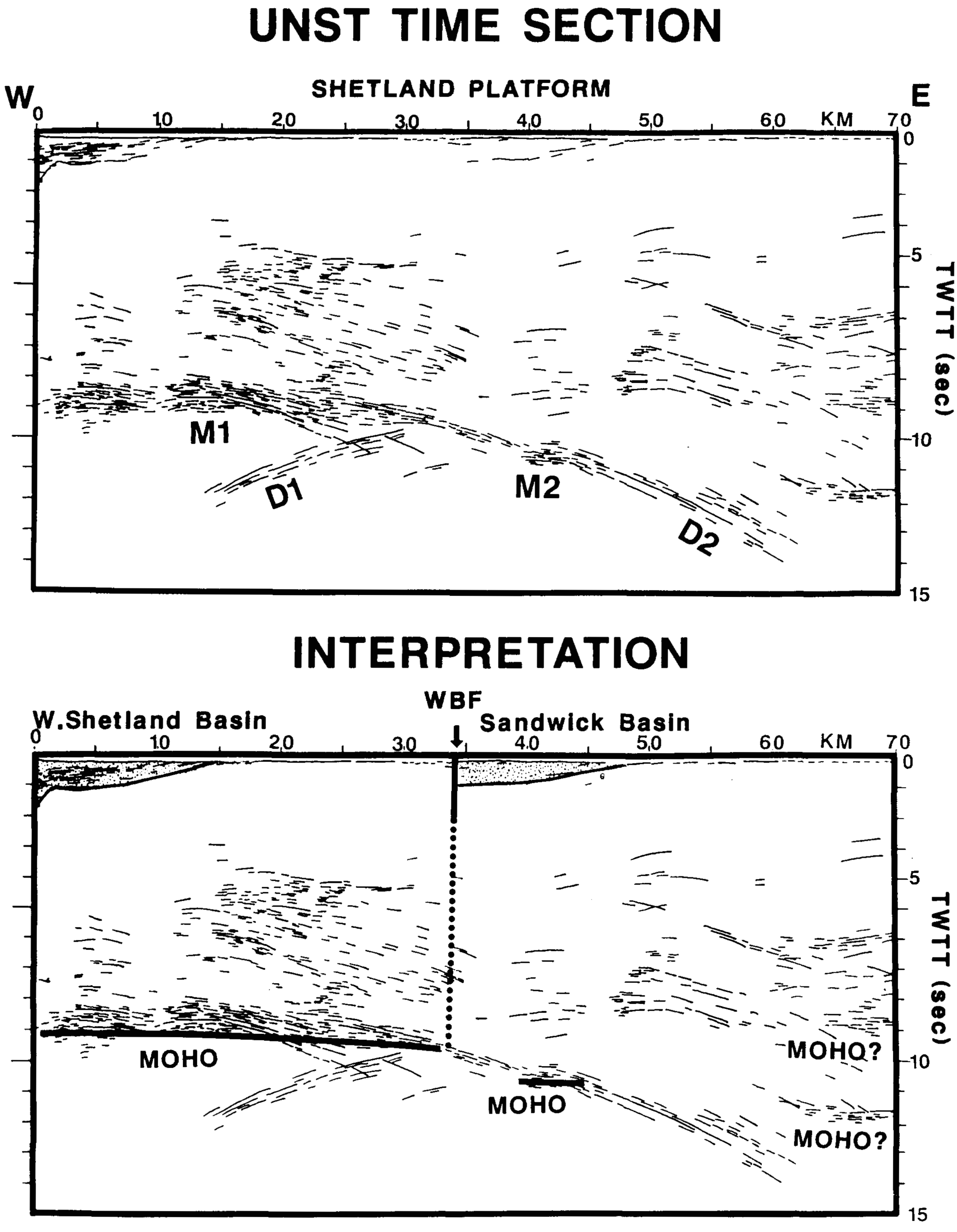

Fig. 2. Line drawing and interpretation of the part of UNST that crosses the Walls Boundary Fault (location in Fig. 1). The downward continuation of the strike-slip fault is shown schematically by a dotted line. Notice the unusual reflections, M1 and M2, and diffractions, D1 and D2. Sedimentary basins are shaded. Scale is 1 : 1 for a velocity of 5 km s^{-1}.

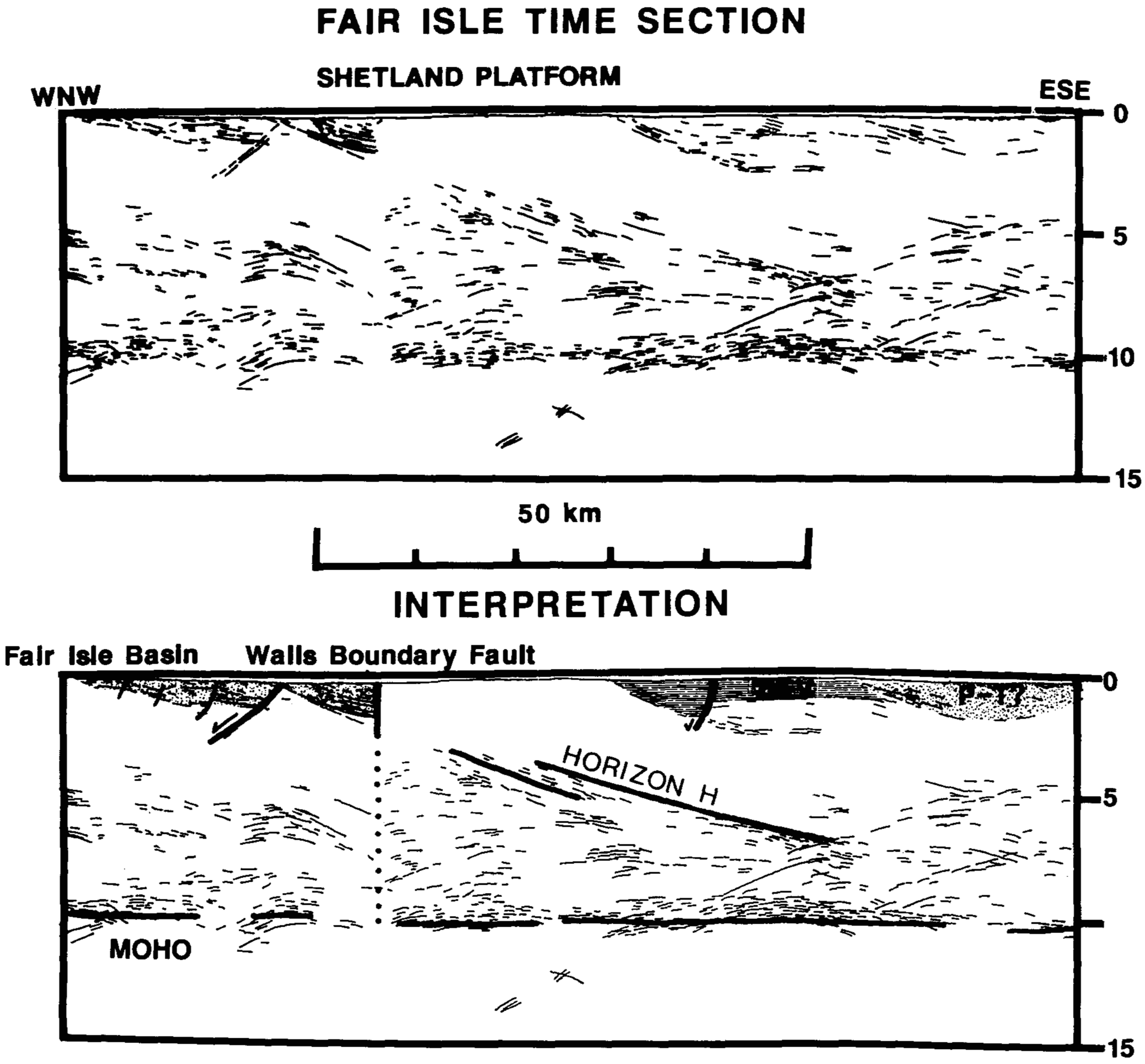

Fig. 3. Line drawing and interpretation of FAIR ISLE across the WBF. (Location in Fig. 1.) The inferred downward continuation of the strike-slip fault is shown schematically by a dotted line. Notice the reflections which comprise Horizon H. Sedimentary basins are shaded. Scale is 1 : 1 for a velocity of 5 km s^{-1}.

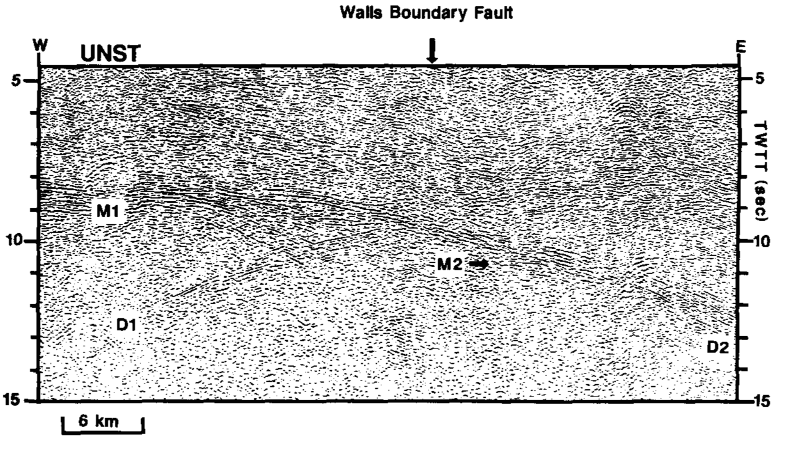

Fig. 4. Reflection data from the lower crust of UNST. Features as described for Fig. 2. Notice the difference in travel-time to the Moho reflections (M1 and M2) on opposite sides of the WBF. Notice also the diffractions D1 and D2. Scale is 1 : 1 for a velocity of 5 km s^{-1}.

Moho of 1.5 s over a horizontal distance of less than 6 km and the location of the two large diffractions occur directly beneath the surface trace of the WBF. The UNST profile therefore shows the WBF north of Shetland to be a vertical structure which probably penetrates the entire continental crust.

The FAIR ISLE profile

The FAIR ISLE profile crosses the WBF just north of the small island of Fair Isle about 39 km south of the Shetlands (Fig. 1). The profile lies on the Shetland Platform within the Caledonian orogen, east of the Caledonian front as identified by Andrews (1985), and runs from the western margin of the Fair Isle Basin to the eastern edge of the Shetland Platform (Fig. 3).

The data quality of FAIR ISLE (Fig. 3) is excellent east of the WBF, where the entire crustal column is imaged with a well-defined Moho at the base. West of the WBF, the Moho is still easily discernible although complexities in the surface structure and large diffractions from the fault itself have either scattered or obscured deeper reflections, thereby resulting in a lower signal-to-noise ratio at depth. The Moho events, however, lie at approximately the same travel-time on either side of the fault (events M3 and M4 on Fig. 3), which suggests that there is no abrupt change in crustal thickness or velocity across the WBF in this region. The strike-slip fault may of course still cut the entire crustal thickness without creating the corresponding Moho structure and seismic signature seen on UNST.

Shallower in the section, several features show evidence of transcurrent strike-slip movement on the WBF. West of the WBF, FAIR ISLE shows the faulted half-grabens of Permo-Triassic sedimentary rocks which comprise the Fair Isle basin. West-dipping listric faults and east-dipping sedimentary reflections are clearly truncated to the east by the vertical WBF (Fig. 3). On the east side of the WBF, the Devonian exposed at the surface is non-reflective. At depth, however, FAIR ISLE images a set of eastwardly-dipping reflections (Horizon H) which also appears to be truncated by the fault. Horizon H dips 30° to the east and can be traced from about 2.5 s TWTT (*c.* 6 km) to a depth of 7 s TWTT (*c.* 20 km). This horizon forms the top of a wedge of reflective middle and lower crust above which the crust is acoustically transparent. The geological structure responsible for this reflective horizon is uncertain since the horizon does not reach the surface, but an interpretation of H as a reflective Caledonian structure is consistent with the results of the MOIST (Brewer & Smythe 1984) and DRUM (McGeary & Warner 1985) profiles.

Seismic modelling

This section presents results of forward seismic modelling used to constrain the possible crustal velocity structures and Moho geometries that could produce the travel-time image seen at depth on the UNST profile. The primary goal at this stage is to find the simplest geological model which will reproduce the geometry of the UNST reflections. The synthetic sections were therefore calculated using a ray-tracing method, the Advanced Interpretive Modeling System (AIMS, trademark of Geoquest International.) Future work also will include the use of wave-theoretical modelling techniques to try to reproduce the high amplitude of the diffractions and to allow for the effect of the wide Fresnel zone at this depth.

There are three main features on the profile important to the modelling: (1) The different travel-times to the Moho on either side of the WBF; (2) The two diffraction events whose apices are offset in travel-time; (3) The horizontal gap between the identifiable Mohos.

The abrupt offset in travel-time to the Moho could be caused by a true offset in Moho depth across the fault or by a major lateral change in crustal velocities, or by a combination of both. Two types of simple models were therefore tested; those in which the average crustal velocity was held constant across the fault while varying the geometry to fit the observed data and those in which the Moho was held at a constant depth while different velocity structures were tried. Both types of models assume the change to be abrupt across a vertical fault zone with diffraction points located at the WBF intersection with the Moho.

Moho offset

The best fitting of all the models is shown in Fig. 5a. Using an average crustal velocity of 6.0 km s^{-1}, this model incorporates a vertical Moho offset of 2.3 km across the downward continuation of the vertical WBF. A diffraction point is located at both the upper and lower edges of this offset. This offset is superimposed on a more gradual increase in Moho depth from W to E of about 5 km over a distance of 30 km.

Superposition of the synthetic results (Fig. 5b) on the observed data (Fig. 5c) shows a good fit to both the Moho reflection times, M1 and M2, and the major diffraction events, D1 and D2. The ray path geometry of the model may also explain why a gap in Moho reflections is observed just east of the fault (Fig. 5d). Moho offset models incorporating a higher average crustal velocity of 6.2 or 6.4 km s^{-1} and correspondingly thicker crust can also be made to fit the observed Moho travel-times, but the shallower diffraction curvatures produced by these higher velocities fail to fit the observed diffractions.

It is unlikely that the actual structure on the Moho is a vertical offset along a razor-thin discontinuity. The fault zone at the surface is up to 1 km wide and is likely to be at least that wide at depth, and the horizontal resolution of the seismic data is only 3–4 km at these depths. Yet this model suggests that the WBF is a crustal-penetrating vertical shear zone with a width at the Moho of no more than 3 to 6 km.

Velocity pulldown

Given the exposure of Lewisian rocks west of the WBF and Caledonian metamorphic rocks east of the fault, there may be significant lateral velocity variations, at least in the upper crust, which may account for part or all of the offset in travel-time to the Moho and the apices of the diffractions. Unfortunately, crustal velocities in the region of UNST are particularly unconstrained due to the lack of nearby refraction data. The closest experiment, the North Atlantic Seismic Project (NASP) of 1972, suggested an average crustal velocity of 6.4 km s^{-1} (Smith & Bott 1975). The crustal velocity structure and/or thickness in the UNST region north of the Shetlands, however, is clearly different than that profiled to the south-west on NASP, the evidence

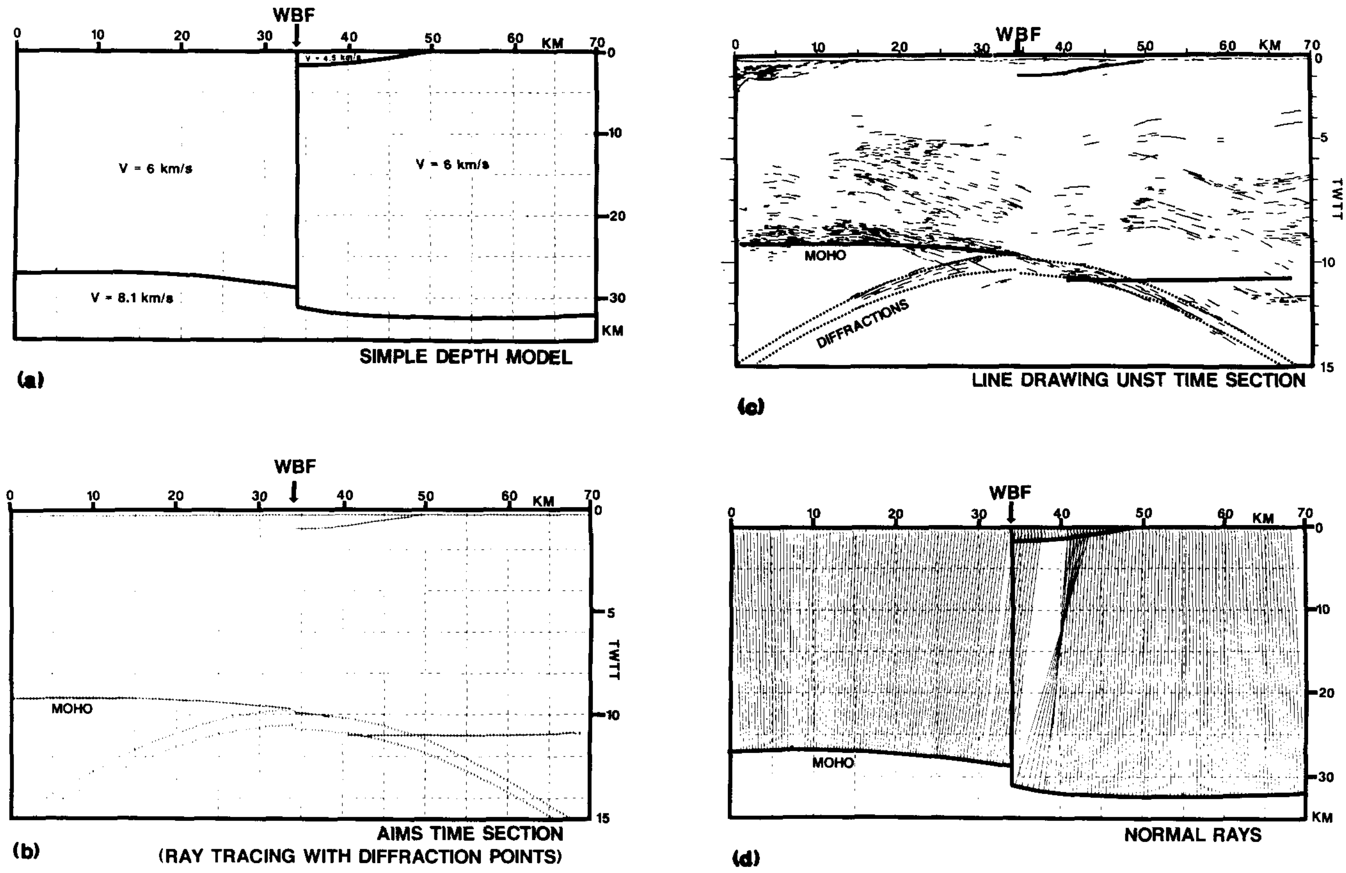

Fig. 5. AIMS synthetic modelling of the deep reflections on UNST. (**a**) The model in depth; diffraction points are located at the intersection of the Walls Boundary Fault and the Moho. (**b**) Synthetic seismogram produced by ray tracing with diffractions. (**c**) Synthetic data superimposed on the line drawing of the profile. (**d**) Path of the rays normal to the interfaces showing small gap in imaged Moho.

being that the reflection Moho time of 9.0–9.5 s west of the WBF is significantly greater than the 8.0–8.5 s Moho that NASP would predict. Moho reflection times consistent with NASP are observed to the south-west on MOIST and DRUM.

Numerous models using two different average crustal velocities on the two sides of the WBF were tested, each maintaining a constant Moho depth and using a higher velocity west of the fault. Although models could easily be constructed to fit the overall change in Moho travel-time from 9.0 s to 10.7 s, none of these models without Moho topography fit the gradual increase of the Moho reflection time from 9.0 to 9.5 s west of the WBF nor do any of the models fit either the curvature of the observed diffractions or the travel-times to the apices of the diffractions as well as the 6.0 km s^{-1} model of Fig. 5.

Furthermore, although more complicated compromise models, incorporating both smoothly varying Moho topography (for example, a gradual crustal thickness increase of 4 km over a horizontal distance of 30 km) as well as lateral velocity variation across the fault, can be constructed to approximate the observed section, none of these complicated models fit the observed diffraction curvature as well as the simple model of Fig. 5.

The major problem with all the models using velocity variation without abrupt Moho structure is the difficulty in generating high amplitude diffractions at the intersection of the WBF, the Moho, and the top of the mantle. For the purpose of the AIMS models, the intersection is assumed to be a point, the vertical boundary between the two velocities a sharp discontinuity, and the average velocity contrast across the fault constant in depth. None of these assumptions are geologically likely. There may well be velocity variation in the upper crust where we observe geological differences at the surface; however, it seems unlikely that there could be a major lateral change in velocity or acoustic properties in the lowermost continental crust just above the Moho.

Assumptions of the modelling

Several assumptions are made in the modelling. First, the reflections at 10.5–11.0 s TWTT east of the WBF are interpreted to be Moho reflections based on their similarity to events west of the fault. If the Moho identification is wrong then the modelling is pointless. Fortunately, the offset of the diffraction apices in travel-time mimics the apparent Moho offset and therefore supports such an interpretation.

The second assumption of the modelling is that events D1 and D2 are truly diffractions from abrupt lateral changes in velocity rather than the focussing of reflected energy such as the 'bow-ties' which synclinal structures produce. This assumption is inherent in the use of selected points as diffraction points within the AIMS model. Such an approach is obviously simplistic given the 3–4 km wide Fresnel zone at this depth. The geometry of any real geological structure on the Moho is certain to be far more complicated than any of the models presented here.

A third assumption is that the source of the diffractions lies at Moho depths. A disruption of the wave field that produces a diffraction at the location of a shallow structure can theoretically produce a diffraction on a deeper continuously horizontal horizon. However, no such shallow structure with shallow diffractions are identifiable on UNST and such a possiblity is considered unlikely given the uniqueness and amplitude of these events.

Results

Forward seismic modelling using AIMS has therefore shown that the geometry of the unusual deep features on UNST (the Moho offset in travel-time, the two diffractions and the lateral gap in Moho reflections) are best fit by a simple model of Moho offset (Fig. 5). In this model, the WBF is a vertical, crustal-penetrating structure which juxtraposes two crusts of similar average crustal velocities (*c.* 6.0 km s^{-1}) but different crustal thicknesses. The Moho depth changes abruptly across the fault by 2.3 km and differs overall by 5 km over a distance of 30 km. The width of the fault at depth is not resolved by either the data or the modelling but is no more than 6 km and may be much less.

Discussion

Very little is known about the nature of strike-slip faults at depth within the more ductile regions below the seismogenic zone. What is the deeper crustal geometry of these faults and how are the large displacements observed at the surface accommodated at depth? Sibson (1983) discusses three possibilities which include downward continuation of the narrow vertical fault into either an equally narrow quasi-plastic shear zone or a shear zone that increases in width with increasing temperature and depth (Fig. 6a & 6b), or decoupling of the steep fault zone into a wide zone of sub-horizontal shear (Fig. 6c). A further possibility (Gibbs 1984) is that the fault zone in the upper crust links into a narrow sub-horizontal detachment fault at mid-crustal depths which transfers the displacement at the surface laterally to another location within the lower crust (Fig. 6d).

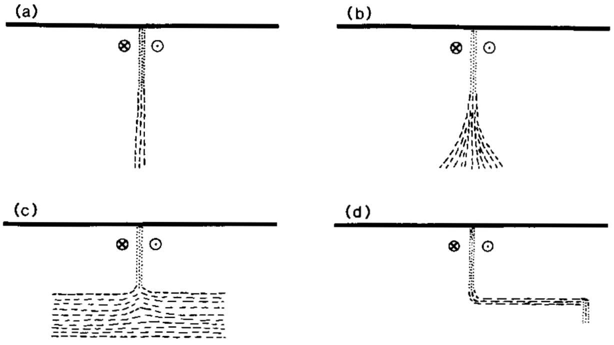

Fig. 6. Possible models for distribution of strike-slip displacement in the lower crust. Models (**a**)–(**c**) after Sibson (1983). (**a**) Shear zone remains nearly constant in width. (**b**) Shear zone widens gradually with increase in depth. (**c**) Shear zone decouples into a wide and thick zone of sub-horizontal shear. (**d**) Shear zone in upper crust links into a narrow sub-horizontal detachment fault at mid-crustal depths which transfers the displacement at the surface laterally to another location within the lower crust.

Existing geological and geophysical data have not yet resolved the question. Field studies of shear zones mapped in inferred middle to lower crustal exposures suggest that some strike-slip faults have remained quite narrow whereas others have clearly widened at depth, with decreasing finite shear strains in the lower crust (Sibson 1983). Xenolithic evidence suggests that at least some major transcurrent faults must penetrate the entire crustal thickness into the mantle. In contrast, geophysical data along the San Andreas fault system, including heat flow, earthquake data, and strain accumulation, suggest that the surface trace and upper crustal faults of the San Andreas plate boundary may be decoupled in the lower crust into a wide zone of shear (Lachenbruch & Sass 1980; Prescott & Nur 1981; Yeats 1981). None of these geophysical techniques provide the high resolution necessary for a detailed description of the nature of strike-slip faults in the lower crust. Only deep seismic reflection data provide such high resolution detail.

BIRPS profiling of the Walls Boundary Fault, a major continental strike-slip fault, provides conclusive evidence that at least one such fault has actually penetrated the entire crustal thickness and may very well continue into the mantle. The high resolution of the technique allows one to determine that this fault, in contrast perhaps to the San Andreas Fault, remains narrow (less than 6 km) and vertical throughout the crust, an example of Sibson's first possibility (Fig. 6a).

The assumed increase in temperature with depth within the crust has therefore not significantly affected the thickness of the Walls Boundary fault zone. One possible explanation is that the crust in this region was particularly cool even at depth during the time of fault movement. Another possibility is that such a crustal penetrating fault zone could itself perturb the temperature or heat distribution in the lower crust and thereby localize movement into a narrow vertical zone.

Both the offset in travel time to the Moho and, in particular, the presence of the two high-amplitude diffractions on the UNST profile suggest not only that the WBF is narrow, vertical and crustal-penetrating, but also that the Moho itself is offset across the fault zone. The use of the term 'offset' is misleading, however, when applied to strike-slip faults. Although the displacement along such a fault may contain some dip-slip movement, the primary component is assumed to have been lateral. The Walls Boundary Fault on UNST north of Shetland has therefore juxtaposed crusts of different thicknesses across the fault, whereas presumably the crustal thicknesses on FAIR ISLE south of Shetland are similar on either side of the fault. Such Moho topography across transcurrent faults may therefore only be a localized feature, depending on the geometry of the Moho prior to movement. Deep seismic profiling may only occasionally detect it.

There have been several recent attempts to profile across major strike-slip faults (Trehu & Wheeler 1987; Cheadle *et al.* 1986; McBride & Brown 1986; Feng & McEvilly 1983 for example), with variable success at imaging the Moho on both sides of the fault. Some of these have shown travel-time differences to the Moho that have been interpreted to be Moho offsets. Such Moho topography may prove to be characteristic of major continental strike-slip structures. Certainly, it is unlikely that the WBF is unique in this respect. It is dangerous, however, to interpret every abrupt change in travel-time to the Moho as a Moho offset, particularly without coincident velocity control. An abrupt change in travel-time to the Moho may, in fact, indicate no real offset in depth but rather major lateral velocity variation shallow in the section. For example, the preliminary analysis of the ECORS northern France profile across the Paris Basin showed a transparent zone beneath the late Variscan Bray strike-slip fault with an apparent offset of the lower crustal and Moho reflections of 0.5–1.5 s TWTT on either side of the fault. This was interpreted to indicate a crustal-penetrating shear zone that offset the Moho in depth (Bois *et al.* 1986). Coincident wide-angle reflection data, however, showed no vertical displacement of reflectors, suggesting that the Moho is actually flat and that the apparent offset is related to shallow velocity variation (Cazes *et al.* 1986).

One of the most interesting results of this survey is that although the age of the Moho offset observed on UNST is unknown, the Moho topography observed on UNST must have been preserved since at least the Cretaceous and probably longer. The crust of the Shetlands is known to have been deformed and intruded not only during the Caledonian orogeny but also during Devonian basin formation. Presumably, the crust was significantly thickened during the orogeny and has since been thinned to its present thickness of about 30 km by either erosion and uplift or lithospheric extension. Geological evidence suggests that most of this thinning occurred before or during the Devonian (Watson 1984).

What is not known is what structural and thermal modifications of the Shetland Platform crust, if any, occurred during the later extensional episodes that formed the North Sea and the Atlantic margin basins surrounding the Shetlands. If one can reasonably assume that the WBF was active either during or between the major late Palaeozoic and Mesozoic extensional events, and it seems unlikely that more than a fraction of the large amount of transcurrent motion necessary to juxtapose crusts of different thicknesses could have occurred after the Mesozoic extension, then the Moho topography on the Shetland Platform has been preserved even during extension in the surrounding basinal regions.

If these later extensional events had in fact been instrumental in thinning or heating the crust of the Shetland Platform, one might have expected the viscosities during extension to have been too low to have supported such Moho topography (Meissner & Kusznir 1986) and lower crustal flow to have occurred, similar to that suggested for the Basin and Range (Gans 1987). The preservation of the Walls Boundary Fault Moho offset, therefore, suggests that the lower crust of the platform remained relatively unmodified both during the Mesozoic extension in the basins and the Mesozoic strike-slip movement on the fault.

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