Nontypical BIRPS on the margin of the northern North Sea: The SHET Survey

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Summary. Striking similarities in the reflectivity of the crust and upper mantle on BIRPS profiles has led to the development of the "typical BIRP", a model seismic section for the British continental lithosphere. The SHET survey, collected in the region of the Shetland Islands and the northern North Sea, fits the general pattern to a certain extent. Caledonian structures and Devonian or younger basins are imaged in the otherwise acoustically transparent upper crust. An unexpected and exciting feature imaged on SHET is a short wavelength structure on the Moho or abrupt Moho offset beneath the strike-slip Walls Boundary Fault. SHET differs markedly from the SWAT typical BIRP, however, by showing a poorly reflective lower crust. Only a narrow zone (~1 s) at the base of the crust contains high-amplitude reflections. The SHET survey therefore highlights the wide variation in lower crustal reflectivity within the total BIRPS data set rather than the similarities.

1. Introduction

In August 1984, the British Institutions Reflection Profiling Syndicate (BIRPS) acquired 830 km of deep seismic reflection data on the British continental shelf around the Shetland Islands. This survey, SHET, comprises six profiles (Fig. 1), each recorded to a two-way travel-time (TWTT) of 15 s (~50 km). More detailed results of this survey will be presented in McGeary et al. (in prep.).

The Shetland region is a geologically complex area. At least two major tectonic events have affected the continental lithosphere during the Phanerozoic: the early Palaeozoic compressional Caledonian orogeny and the late Palaeozoic and Mesozoic continental extension which preceded the actual rifting of the north Atlantic region. SHET primarily images the crust of the Shetland Platform, the northern promontory of the British Caledonian orogen, yet the survey is also located at the juncture between the North Sea extensional basin and the rifted Atlantic margin. Both major tectonic events must have involved significant deformation of the continental lithosphere and have presumably also affected its reflective character.

This paper first presents some of the typical features imaged by SHET in the upper crust of the Shetland Platform. It then discusses the reflective character of the Shetland crust as a whole, particularly the lower crust and Moho. Finally, the implications of the SHET survey results with respect to the concept of the "typical BIRP" are examined.
2. Upper crust

There are three types of features, mapped at the surface of the Shetland Platform, which are imaged by the SHET profiles: eastward-dipping Caledonian structures, major strike-slip faults, and Devonian sedimentary basins. All three features can be related to the Caledonian orogeny or its terminal stages (Watson 1984). Structures and basins imaged on SHET in the upper crust which are related to the later extensional tectonics are not discussed in this paper.

The Shetland Platform shows abundant evidence of Caledonian compressional tectonics (Flinn 1985). Although none of the prominent reflections on SHET can be directly tied to any of the compressional structures mapped on the Shetlands, there are several sets of eastward-dipping reflections which can be interpreted to be Caledonian structures. Unlike similar structures interpreted on the MOIST and DRUM profiles north of Scotland (Smythe et al. 1982; McGeary & Warner 1986), these structures appear neither to be highly reflective nor to have been later significantly reactivated during extension.

By far the most interesting structure crossed by the SHET survey is the Walls Boundary Fault (WBF). This fault forms a major structural discontinuity in the Shetlands (Flinn 1977) and is probably the most significant of the several possible northern extensions of the Great Glen Fault (Fig. 1), a major late Caledonian strike-slip fault in Scotland. The amount and timing of movement on each fault is highly controversial (see Smith & Watson 1983), but the transcurrent displacements are undoubtedly large, at least 100-200 km of sinistral offset on the Great Glen Fault before the end of the Devonian (Smith & Watson 1983) and 65-90 km of post Middle Devonian dextral offset on the WBF (Flinn 1977; Astin 1982).
The SHET survey crosses the WBF twice (Fig. 1). South of the Shetlands, reflections from a sedimentary basin west of the fault and east-dipping reflections interpreted to be a Caledonian structure east of the fault are both truncated by the WBF. The reflection times to the Moho, however, do not appear to be significantly different on either side of the fault.

In contrast, the SHET profile north of the Shetlands reveals a surprising set of reflections (Fig. 2) which suggests that the WBF is a near-vertical structure which penetrates the entire crustal thickness and offsets or abruptly warps the continental Moho. The Moho reflection time changes from ~9 s to ~10.5 s across the fault zone. Even more indicative of Moho structure are the two high-amplitude, diffraction-shaped events which originate at Moho depths and collapse at crustal velocities. These events suggest a very short wavelength structure on the Moho located directly beneath the surface location of the strike-slip Walls Boundary Fault. This structure has been preserved since at least the Cretaceous, the latest possible time of movement on the fault.

The third feature of the upper crust on SHET, the Devonian basins, have complex structure and are not particularly reflective. Their most striking characteristic on SHET is that they seem to damage seismic penetration to deeper levels of the crust, making the Shetland Platform a technically difficult area in which to profile the lower continental crust.

3. Lower crust and Moho

The lower continental crust of both the Shetland Platform and the northern North Sea is not particularly reflective as imaged on SHET, except near the base of the crust where there is often a band of high-amplitude reflections about 1 s thick. The base of this bright band is interpreted to be the continental Moho (Matthews & Cheadle 1986). Lower crustal reflections are generally not very continuous, either chopped into short segments or diffractive, and the reflectivity is often concentrated into two or three discrete horizontal layers at different travel-times separated by transparent zones. An example of the most reflective lower crust imaged on SHET can be seen in Fig. 2 west of the WBF.

![Figure 2](https://academic.oup.com/gji/article-abstract/89/1/231/672875)

Figure 2. An interpreted line drawing of part of the profile north of the Shetlands (UNST profile). The surface location of the strike-slip Walls Boundary Fault (WBF) is marked as well as the possible Moho locations, interpreted to be the base of the narrow zone of bright reflectivity. Notice the two prominent sets of curved events which seem to originate at Moho depths beneath the WBF.
upper crystalline crust is not reflective at all and the lower crust is only moderately so. The Moho reflection band is quite continuous and bright but the local Moho topography in travel-time is itself uncommon.

4. Discussion and conclusions

The results of early BIRPS surveys, particularly WINCH, prompted the creation of an imaginary average seismic section of the British continental crust, the "typical BIRP" cartoon.
Nontypical BIRPS on the margin of the northern North Sea: The SHET Survey (Matthews & Cl 1986). This cartoon (centre of Fig. 3a) shows an upper crust largely devoid of reflect except those from either sedimentary basins or medium to low-angle structures, and a highly reflective lower crust with the Moho at the base of the reflectivity. The upper mantle is transparent with the exception of occasional dipping reflections.

Figure 3 (b). Classified into types interpreted to be structural in origin (Warner & McGeary, this issue).
interpreted to be structural in origin (Warner & McGeary, this issue). SWAT spectacularly reinforced the apparent validity of this cartoon and confirmed its usefulness as a working model.

In contrast, the SHET survey exhibits a few significant departures from the "typical BIRP." Most striking is the poor reflectivity of the lower crust compared to that of SWAT or WINCH. Those lower crustal reflections which do exist tend to be quite short or diffractive. In addition, although there is still a distinction between the "blank" unreflective upper crust and the reflective lower crust, the top of the reflectivity is highly variable and difficult to pick, perhaps a problem in signal penetration. The notable exception to the poor reflectivity is the narrow (~1 s), highly reflective zone at the base of the crust. The abrupt difference in travel-time to the Moho across the WBF is also quite unusual for a BIRPS profile; the Moho typically remains at a fairly constant travel-time regionally or on the scale of a single section (Warner, in press).

Although in an area new to BIRPS, SHET was acquired and processed in a way very similar to the WINCH and SWAT surveys (Brewer et al. 1983; BIRPS & ECORS 1986), especially SWAT. Therefore, the differences evident in the reflective character of the lower crust and Moho on SHET compared to WINCH or SWAT cannot be directly ascribed to differences in processing or acquisition. Such differences therefore must be caused either by local problems in signal penetration and/or noise or by actual variation in the underlying crustal geology. The high amplitudes of the Moho reflections on SHET beneath the poorly reflective lower crust suggests that variation in the lower crustal geology rather than noise is the primary cause.

The question then arises whether the concept of the "typical BIRP" should be discarded in light of the differences evident on the non-typical SHET profiles. In defence of the concept, I would suggest that SHET merely highlights the variation in lower crustal reflectivity - the continuity, amplitude, thickness, and distribution of the reflections - in a particularly dramatic way and represents not so much a departure from the normal crustal profile as an end member of a continuum of crustal images. With over 8000 km of deep seismic reflection data in a geologically complex region the size of the Basin and Range, the lower crust of Britain may be the most densely sampled in the world. With such sampling, the method of classification becomes a philosophical point, similar to that which may arise when classifying fossils within an evolutionary continuum or when deciding when to stop dividing tectonostratigraphic terranes. One can either use a descriptive model for the reflectivity of the lower crust general enough to include all variation (a "lumper"; Fig. 3a) or alternatively try to divide or bin different profiles into separate types (a "splitter"; Fig. 3b) It is certainly not clear which method of classification is the most useful in this case.

In conclusion, the concept of the "typical BIRP" highlights the similarities between profiles in the BIRPS data set. In general, the crystalline upper crust is not reflective with the exception of basins and faults; the lower crust is reflective to variable degrees, with a variable top to the reflectivity but almost always a well-defined base, the Moho.

The SHET survey, however, highlights the variation within the BIRPS data set. This variation can itself prove to be quite interesting. For example, an analysis of the whole data set shows that the variation in lower crustal reflectivity cannot be directly related to different tectonic provinces. There are no identifiable abrupt boundaries between the Caledonian foreland and orogen, between Variscan and Caledonian crust, or between the Caledonides and the extended crust of the North Sea. Finally, before any conclusions can be derived from this variation, it is imperative that we better understand the effect of noise generated at shallow depths in the crust on the image at depth, and also the petrologic and physical nature of deep reflectors.
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