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Internal structure of the Erlend Tertiary volcanic complex, north of Shetland, revealed by seismic reflection

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SUMMARY: Detailed seismic reflection mapping 100 km N of Shetland has revealed a large subcrop of Palaeocene basalts proved by exploration drilling. The geometry of internal reflectors within the buried basalt suggests the existence of two partially eroded volcanoes. A vent of about 2 km in diameter, surrounded by radially outward-dipping basalts, is centred over the Erlend igneous complex, whose existence had been postulated previously on gravity and magnetic evidence alone. A new volcano, the more deeply eroded West Erlend centre, is postulated by interpretation of seismic data and by gravity modelling. An approximately cylindrical mafic or ultramafic pluton is inferred from the gravity modelling to underlie each of the two centres; the diameter of the Erlend pluton is about 14 km and that of West Erlend about 5–7 km. The seismic stratigraphy of volcanic rocks can now be recognized as a valid new field of study with particular relevance to hydrocarbon exploration.

A previous interpretation of offshore gravity and magnetic data surveyed by IGS in 1977 suggested the probable existence of a Tertiary igneous complex at approximately 61°50′N, 00°30′W (Chalmers & Western 1979). This complex has since been named the Erlend igneous complex* (Ridd 1983). It is situated in the northern parts of quadrants 208 and 209, which are shown in Fig. 1. The present study, based on Western Geophysical and BGS marine gravity data, together with 6000 km of commercial multichannel seismic data mapped at 1 : 50000 scale, has allowed us to elucidate the structure of the Erlend complex, and postulate the existence of another smaller mafic plutonic body. This body, which we call the West Erlend centre, is situated about 30 km to the W of the Erlend pluton, at approximately 61°53′N, 1°00′W.

The age and regional distribution of the Tertiary basalts in the Faeroe-Shetland region has been discussed elsewhere (Smythe 1983; Smythe *et al.* 1983). The Faeroe-Shetland Escarpment, which subcrops to the N of the present study area (Fig. 1), marks the SE edge of the thick early Eocene Middle Series of basalts exposed in the Faeroes. The scarp may have resulted from rapid cooling and freezing of basaltic lava flows as they reached the contemporary shoreline (Smythe *et al.* 1983). The underlying Lower Series basalts of late Palaeocene age extend beyond the scarp, providing a strong reflection (Smythe *et al.* 1983, fig. 5) which can be traced across the Faeroe-Shetland Trough into the northern parts of quadrants 208 and 209 (Fig. 2).

Britoil well 209/9-1, drilled in late 1979, proved the existence of a considerable thickness of basalt and rhyolite (Fig. 3, redrawn from Ridd 1983). The basalts are of Palaeocene to early Eocene age and are described as 'probably quartz tholeiites', whereas the underlying rhyolites are believed to be late Cretaceous (?Campanian) in age (Ridd 1983). BP wildcat 208/15-1A, also drilled in late 1979, did not encounter the Palaeocene basalts or ?Campanian rhyolites, but did encounter gabbroic sills intruding early Tertiary sediments. It is possible, using seismic mapping to delineate the thickness and extent of the Tertiary basalts and sediments, to suggest the size and depth of the proposed mafic plutons using gravity modelling techniques.

Structure and extent of the basalts

The basalts in the northern part of quadrants 208 and 209 (Fig. 2) have been mapped at a scale of 1:50000, using 6000 km of unmigrated commercial seismic reflection data. The top of the basalt, which lies between 1 and 3 km below sea level, usually produces a very strong reflection clearly distinguishable from the adjacent sediments. The edge of the basalt is frequently represented by an abrupt change in character of the seismic reflector (Fig. 4, line A). Locally the change in character is a more gradual feather-edge (Fig. 2), making interpretation difficult. In some areas, the edge is marked by a pronounced scarp (Fig. 4, line B) reaching heights of up to 250 m. The escarpment is best developed in the SW and NE of the basalt subcrop (Fig. 2), and may represent an earlier palaeo-shoreline comparable in origin with the Faeroe-Shetland Escarpment.

The basalts generally mask good reflections from deeper seismic events. The sudden increase in seismic penetration, which produces an increase in reflections from sills, is also diagnostic of the edge of the basalts.

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* We prefer the original spelling Erlend, after the Norse king, rather then the anglicized version Erland previously proposed (Ridd 1983).

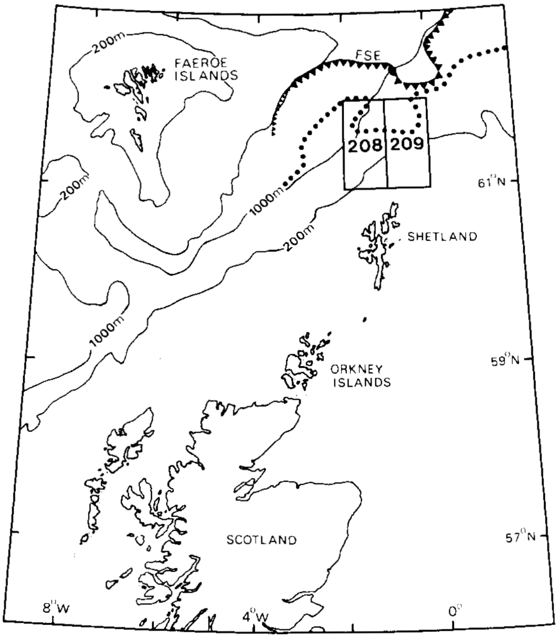

FIG. 1. Location map of Quadrants 208 and 209. FSE—Faeroe-Shetland Escarpment. Dots indicate SE limit of late Palaeocene basalts.

The base of the basalts cannot be mapped in detail, as the seismic reflection is not clear. The thickness (proved in 209/9-1) in the central area of the subcrop, together with feather edge of the top basalt horizon, are the main constraints. Where identifiable, the base basalt reflector is a 'black–broad white–black' reversed polarity event (Fig. 4, lines A–E).

The structure over Erlend is illustrated by the three seismic profiles (Fig. 4, lines C–E) which reveal the central vent of the volcano. Seismic line H (Fig. 2; reproduced in Ridd 1983, fig. 9) also shows a depression at its NW end corresponding to the southern flank of the vent. The four lines show that the vent is roughly circular in plan, with a diameter of about 2 km and a depth of 300–400 m. Around the vent, the intra-basalt reflectors consistently dip away from the vent in a radial pattern. Relative to the nearly flat erosional upper surface of the basalts, which has a slight downward tilt to the N, the intra-basalt dips are greatest (about 20°) near the vent, flattening out to zero some 5–10 km distant from it. We suggest that the radially-dipping structure represents the attitude of deposition of lava flows and pyroclastic material erupted from an originally conical-shaped volcano, the uppermost part of which has been planed off by erosion. An alternative, tectonic, origin for the internal structure of the lava pile, envisaging a later pluton 'punching' its way through the basalts, we

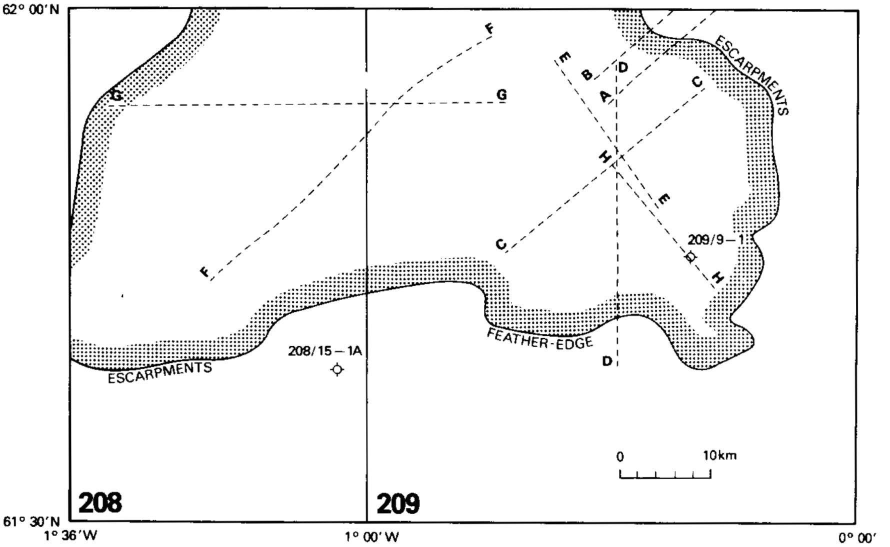

FIG. 2. Subcrop of Tertiary basalts (stippled) in the northern parts of Quadrants 208 and 209, based on the interpretation of 6000 km of seismic reflection sections. Dashed lines A–G are seismic lines shown in Fig. 4. The labels 'Escarpments' and 'Feather-edge' indicate the local character of the edge of the basalts. Line H is reproduced in Ridd (1983, fig. 9).

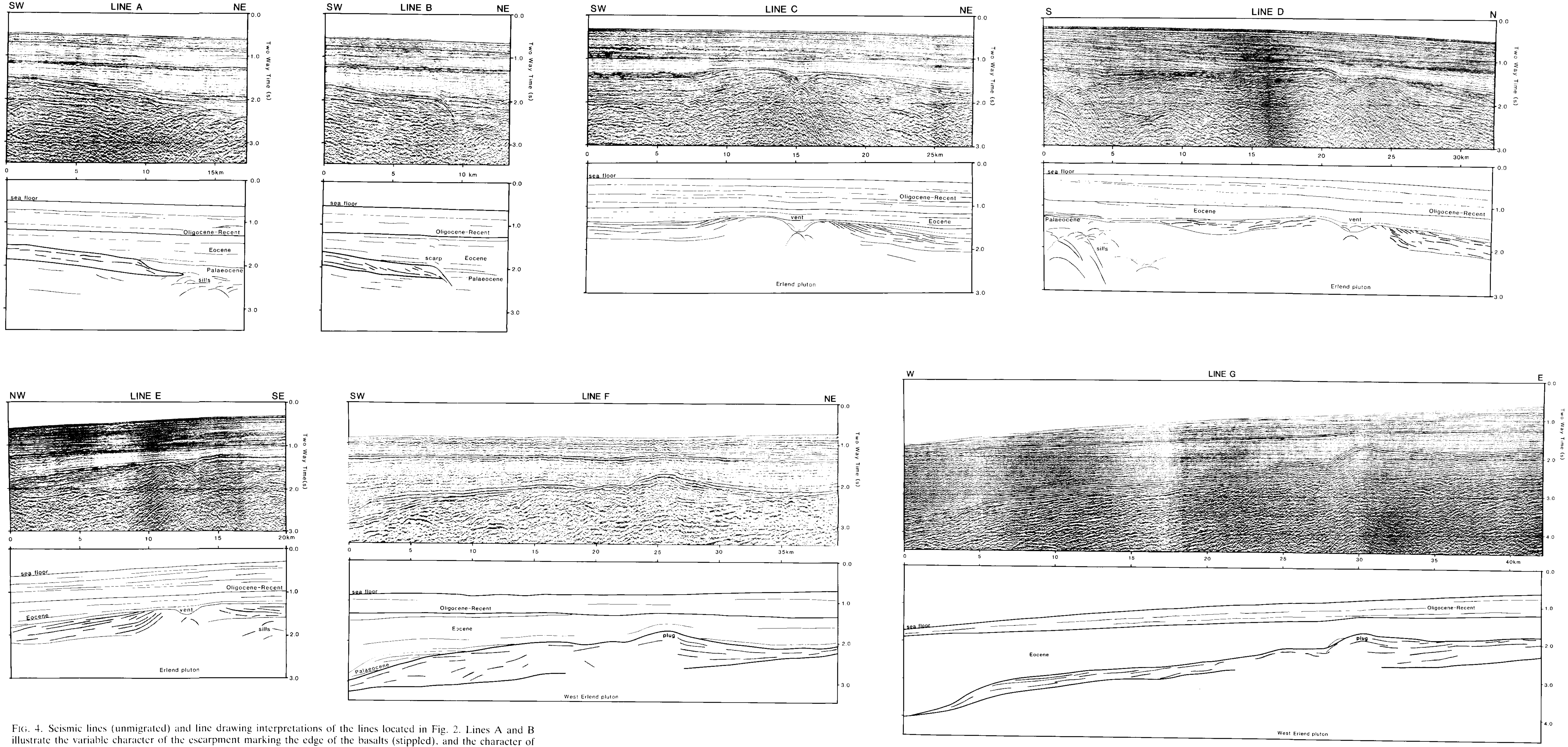

FIG. 4. Seismic lines (unmigrated) and line drawing interpretations of the lines located in Fig. 2. Lines A and B illustrate the variable character of the escarpment marking the edge of the basalts (stippled), and the character of the intra-Cretaceous sill complex. Lines C–E run through the main Erlend vent, and demonstrate the intra-basalt dips away from the vent. Lines F and G cross the West Erlend centre, intersecting at the plug situated on the NE flank of the more deeply eroded volcano.

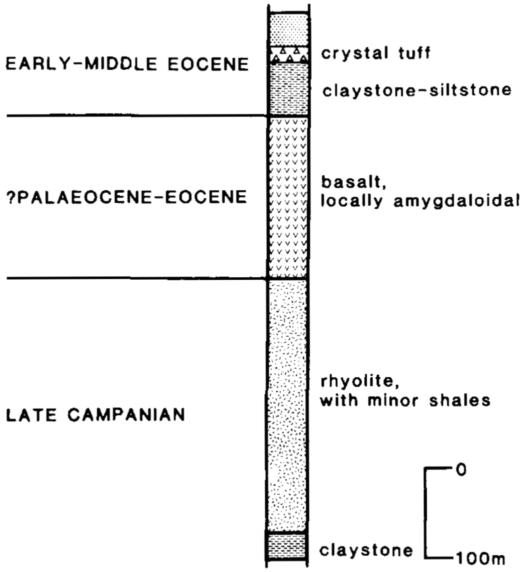

FIG. 3. Stratigraphic column (redrawn and simplified from Ridd 1983) of the volcanic rocks encountered in 209/9-1 on the SE flank of the Erlend volcanic centre (for location see Fig. 2).

find untenable, because:

(1) There is no tectonic disturbance of the immediately overlying Eocene cover,
(2) Erosion of the pluton would leave a resistant neck rather than the observed depression, and
(3) It leaves the source of the basalts unaccounted for, and relegates to chance the central location of the pluton below the lobate subcrop of lavas in quadrant 209.

The structure of the West Erlend centre is less clear, in that there is no vent or radially-dipping basalt structure (Fig. 4, lines F and G). Instead, there is a zone overlying the pluton (postulated from gravity modelling) with no consistent intra-basalt reflections. The circular high shown on lines F and G (Fig. 4) may be a small volcanic plug, located on the NE flank of the centre, although there does appear to be some internal layering. The relief around the plug suggests that considerable erosion, possibly up to a kilometre, of the basalt has occurred; this would account for the present-day absence of a vent and radially-dipping basalts.

The structure of the Erlend complex is unique amongst the Tertiary igneous complexes of NW Britain. Nowhere else has such a high structural level been preserved. The dipping basalts of the central cone around the vent, which flatten out into a shield-like volcano at 5–10 km from the vent, compare with the Beerenberg Volcano, Jan Mayen (Fitch 1964). In Beerenberg the central cone is about 5 km across and depositional dips within the basalts approach 45°. The remains of the central cone of Erlend are somewhat larger in area and the preserved depositional dips are lower than those of Beerenberg. This could be consistent with a less viscous lava and/or a higher rate of effusion.

In general the main Ash Marker of the North Sea (Jacqué & Thouvenin 1975) can be mapped as a lateral equivalent at the top basalt reflector. Around the SE flank of Erlend there is an area where the Ash Marker onlaps onto an area of basalt. The Ash Marker does not, however, cross the steeply dipping lavas around the vent. This suggests that the Ash Marker is slightly younger than, or about the same age as the last eruptions from Erlend. Together with the Faeroes and the large scale fissure eruptions, as represented on Greenland by the Blosseville Volcanics Group (Soper *et al.* 1976), Erlend could be a source of the widespread series of late Palaeocene to early Eocene ash falls seen over much of the North Sea, culminating in the Balder Formation (Deegan & Scull 1977). These ash fall units have also been shown to occur in the West Shetland Basin (Ridd 1983), the Rockall Trough (Jones & Ramsay 1982), SE England (Knox & Ellison 1979) and Denmark (Pederson *et al.* 1975).

Gravity interpretation

A provisional free air gravity anomaly map has been compiled using BGS and Western Geophysical marine gravity data (Fig. 5). We have not corrected the apparent static shift between the two data sets of 2–3 mGal, which is probably due to the use of different reduction formulae.

Five geological cross-sections (Fig. 6) have been constructed across the area using seismic coverage. Each time cross-section has been converted to depth using the velocities shown in Table 1, derived from calibrated well velocity logs and from company seismic data. The basalts have an unusually low interval velocity of about 3.5 km s^{-1}, possibly because the pile has been built up by extrusion of thin flows (Ridd 1983, fig. 8), each in turn being subaerially weathered before burial by the next.

The gravity effect of the sea water and basalt is computed for each cross-section using a two dimensional gravity program, in which the two layers are approximated by prisms extending to infinity in both directions normal to the plane of the model. This approximation for calculating the gravity effect is valid to better than 1%, as even the deeper basalt prism models (Fig. 6) are very shallow (1–3 km depth) in relation to their horizontal extent in the directions normal to the plane of the cross-sections, which is of the order of 30–70 km. A density contrast of 500 kg m^{-3} between the basalts and the surrounding Tertiary and Mesozoic sediments, and -1200 kg m^{-3} between the sea water and sediments is assumed. Although the basalt P-wave velocity has been observed to be very

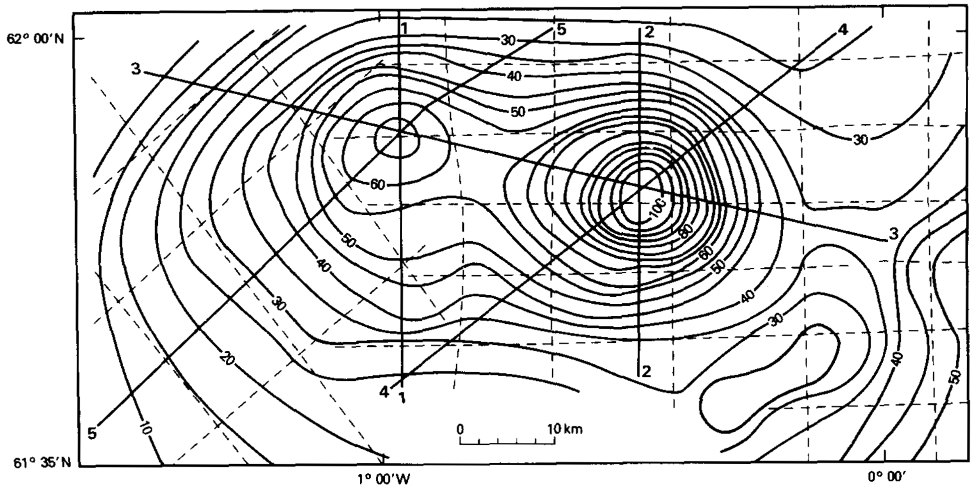

FIG. 5. Provisional free-air gravity anomaly map of the Erlend and West Erlend centres, compiled from BGS data (dashed lines, N–S & E–W grid) and Western Geophysical data (dashed lines, diagonal grid). Contour interval 5 mGal. Profiles 1–5 are used in 2-D modelling (Fig. 6).

TABLE 1. *Seismic interval velocities and assumed densities*

Interval	*P-wave velocity* *(km s^{-1})*	*Density* *(kg m^{-3})*
Sea water	1.48	1030
Oligocene-Miocene	1.95	2230
Palaeocene-Eocene	2.15	2300
Tertiary basalts	3.50	2800

low, we have retained the density usually assumed for basalt (Table 1), as we have no direct evidence that it too is lower than normal. If it also is lower, then our computed gravity effect of the basalt layer (Fig. 6) will be somewhat too high. From the observed and calculated gravity profiles of Fig. 6, a stripped-free air gravity anomaly map can be produced (Fig. 7) showing the observed gravity, corrected for the effect of the sea water and the basalts. Note that the assumptions and approximations discussed above will tend to produce residual anomalies that are likely to be somewhat underestimated. Next, a planar regional anomaly is subtracted, producing a residual anomaly map (Fig. 8). The strike of the regional gradient is approximately parallel to the edge of the West Shetland platform, with the anomaly increasing to the WNW at 0.3 mGal/km (Fig. 8). This gradient can be accounted for by crustal thinning towards the WNW, as the continental crust of about 27 km thickness in the SE, below the Shetland Platform, passes laterally into thin, quasi-oceanic crust about 8 km thick, beneath the Faeroe-Shetland Trough (Smythe *et al.* 1983; Bott & Smith 1983). The final residual anomaly map (Fig. 8) shows two pronounced circular gravity highs approximately situated over the two centres defined on seismic evidence.

Three-dimensional modelling of the postulated igneous bodies has been carried out to match the residual anomalies. Each body is approximated by vertical concentric cylinders, our preferred models being shown in Fig. 9. The two centres are about 30 km apart; at that distance the gravity effect that each has on the other is of the order of 1 mGal. The density contrast used in the upper parts of the plutons is 500 kg m^{-3}, being the same contrast as that used for the basalts. For the deeper cylinders, 300 kg m^{-3} is used, representing the expected contrast in density between gabbroic or ultramafic intrusives and continental crust.

Our preferred model for the Erlend pluton requires a diameter of 14 km, with the base at 15 km (Fig. 9). The least well defined parameter is the depth to the base of the pluton. Adding 5 km to the base increases the anomaly by 5 mGal, whereas a similar increase in anomaly is obtained by increasing the diameter by 2 km. The model (Fig. 9) is not dissimilar to that proposed by Chalmers & Western (1979).

The gravity anomaly over the West Erlend pluton has a similar wavelength but a lower amplitude than that of the Erlend pluton. A model with a vertical cylinder having a density contrast of 300 kg m^{-3}, with a broader top and a narrower base, gives a satisfactory fit (Fig. 9). The broad top to the model shape should not be taken to represent a mushroom-shaped pluton, but probably suggests that there is a thicker sequence of basalts above the pluton, which has not been recognized by our seismic mapping. Two models are

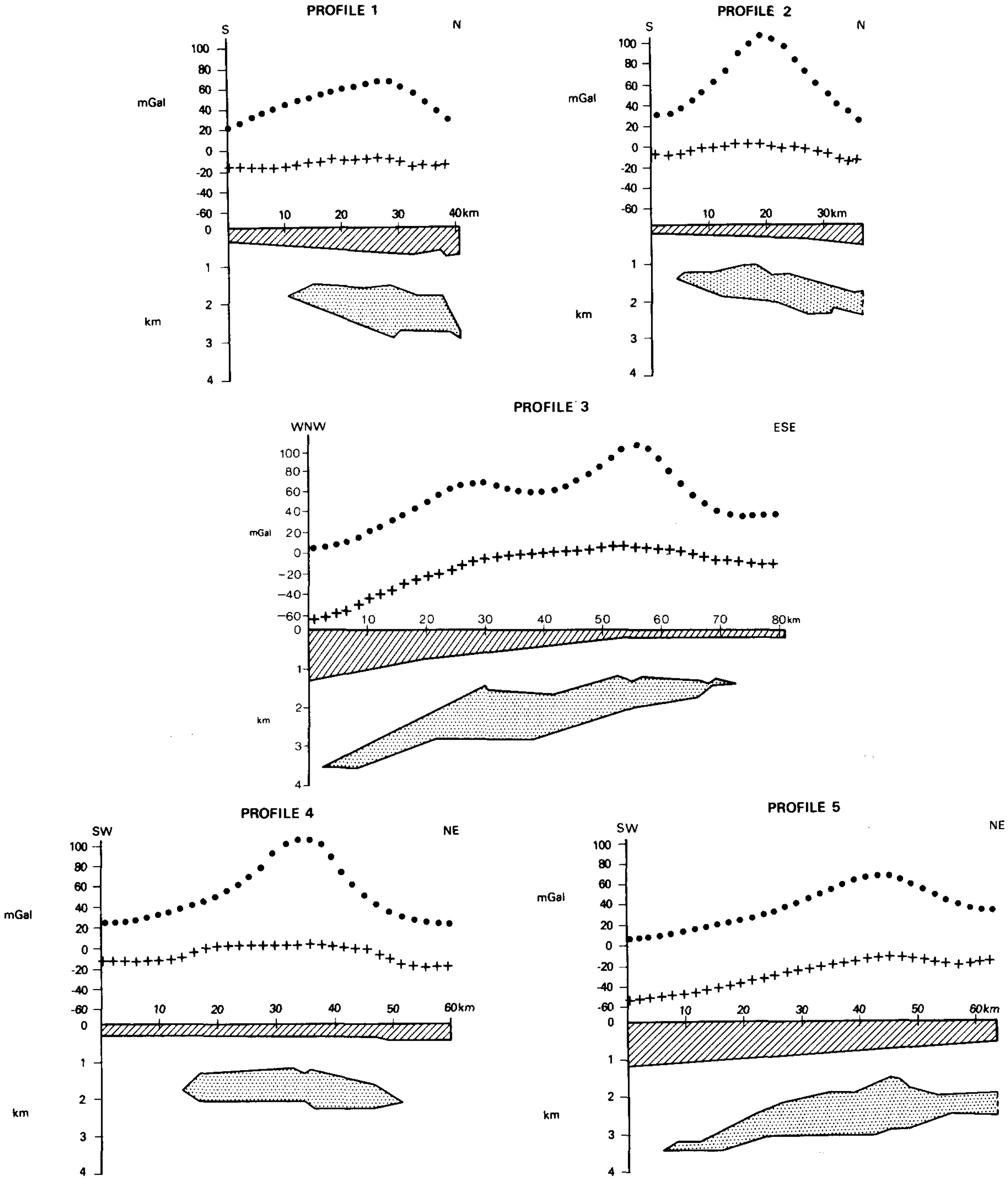

FIG. 6. 2-D profiles (located in Fig. 5) used to remove the gravity effect of basalts (stippled) and sea water (diagonal lines), having density contrasts of 500 kg m^{-3} and -1200 kg m^{-3}, respectively, relative to the surrounding sediments. Observed free-air anomalies along the lines of section (dots) are displayed above the profiles together with the anomaly (crosses) calculated for the combined effect of basalt and sea water. Profile 2 corresponds in part to seismic line D (Fig. 4), and similarly Profile 5 to line F.

shown, the first with a base at 15 km and a diameter of 5 km, the second with a base at 8 km and a diameter of 7 km. Either model is acceptable, illustrating the limitations of the gravity modelling in the absence of other constraints.

In overall dimensions (excess mass, diameter, etc.) Erlend is similar to the Tertiary igneous centres of Mull and Skye (Bott & Tuson 1973). West Erlend is much smaller, but of the same order of size as Rhum (McQuillin & Tuson 1963) and Ardnamurchan (Bott & Tuson 1973).

Discussion

The former sub-aerial expression of the Erlend complex is now represented by the partially eroded conical volcano which built up an extensive pile of tholeiitic flood basalts during the late Palaeocene. Earlier, probably more localized silicic activity began in the Campanian (Ridd 1983). The doming of the eroded surface of the basalts, producing the large closure of 30000 acres (once considered to be a hydrocarbon prospect) is probably the result of

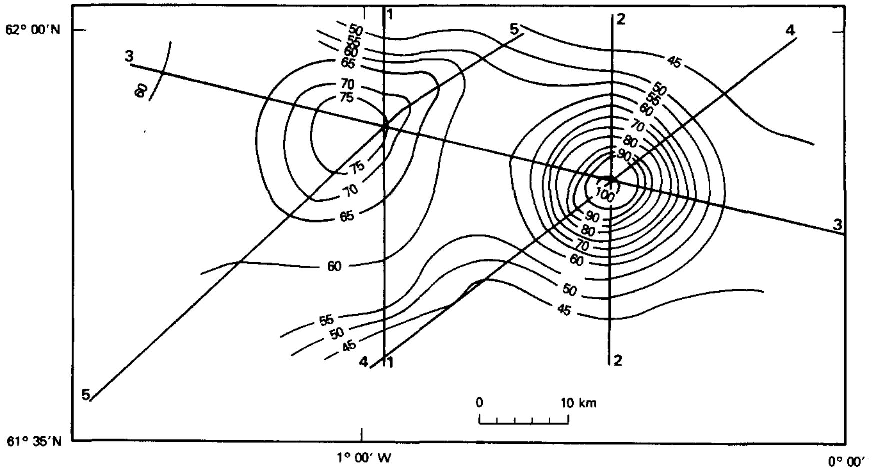

FIG. 7. Stripped gravity anomaly map constructed from data along profiles 1–5 (Fig. 6). The buried Tertiary basalts and sea water layers have been 'replaced' by sediments. Contours in mGal.

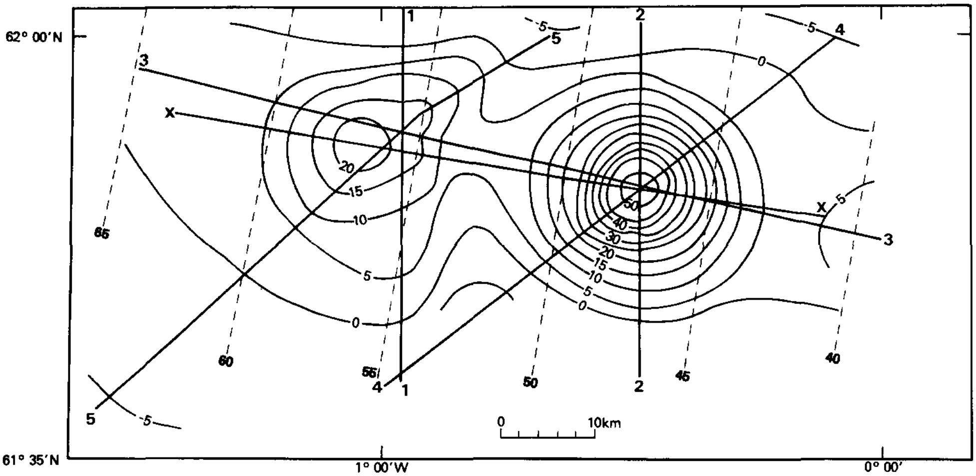

FIG. 8. Residual stripped gravity anomaly map produced by removing the planar regional anomaly (dashed lines) from the stripped map (Fig. 7). The regional anomaly is due to crustal thinning from the Shetland platform (E) to the Faeroe-Shetland Trough (W). Contours in mGal. Profile XX is used in 3-D modelling of the pair of circular anomalies (Fig. 9).

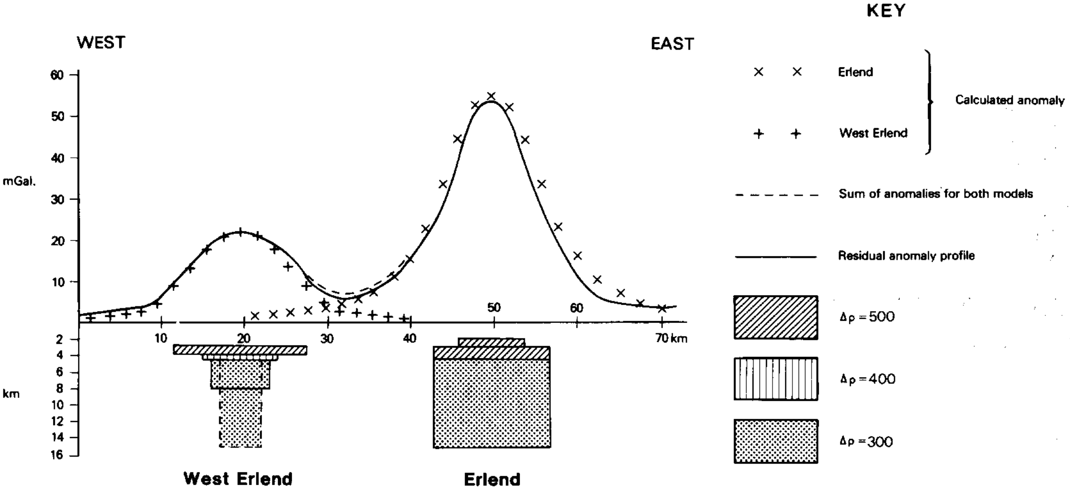

FIG. 9. Residual gravity along profile XX of Fig. 8, compared with computed gravity of concentric vertical cylinders below the Erlend and West Erlend centres. The dashed cylinder below the West Erlend centre is an alternative to the lowest cylinder with its base at 8 km depth. Density contrasts are in kg m^{-3} with respect to surrounding sediments and crust (see text).

differential compaction around the underlying 14 km diameter pluton. The West Erlend centre is more deeply eroded and also more complex, in that a resistant plug is located on the flank of the main centre identified from gravity. The residual gravity map (Fig. 8) also reveals this asymmetry.

The 53–55 Ma age of the main phase of basalt eruption from the Erlend centres is several million years younger than the age of plateau basalt eruption of the Hebridean Tertiary igneous centres. It is, however, approximately coeval with the late phase of major explosive activity in the Hebrides inferred from the recent recognition of welded tuffs and ignimbrites in several of the Hebridean centres (B. Bell and R. N. Thomson, pers. comm.). Therefore the several Hebridean centres could also have provided material for the Palaeogene ash beds of the North Sea region, in addition to the Faeroe-Shetland volcanic province, of which Erlend is a part.

Our study of the Erlend complex is the most direct evidence yet put forward for the volcanic structure of a British Tertiary igneous centre. The mapping of reflection structure within a buried volcanic complex is, we believe, completely new, and made possible only by the advances in the seismic reflection method of the last five or six years; prior to this, basalt flows and other igneous rocks would conventionally have been recognized on seismic sections by their acoustic impenetrability. A new aspect of reflection interpretation—the seismic stratigraphy of volcanic rocks—can now be developed. For example, the discrimination of prograding lava flows from delta foresets on reflection sections will be of the utmost importance in the evaluation of hydrocarbon prospects, particularly on the continental shelves near passive margins where extensive flood basalts are common.

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