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June 1981

NATURAL ENVIRONMENT RESEARCH COUNCIL

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INTRODUCTION

Although many passive margins appear to be characterised by listric faulting, it has become clear that this is by no means always the case and a second type may exist. This type is characterised by the absence of listric normal faults and by the presence of thick sequences of strong, oceanward dipping reflectors. These reflectors are now recognised on many passive margins, and in general comprise a sequence that usually underlies, and occasionally truncates against a strong, sub-horizontal smooth reflector generally interpreted as marking the transition between rifting and spreading. They have also been identified within oceanic crust immediately adjacent to the continent-ocean boundary. Although now widely recognised, the origin of the dipping reflectors is enigmatic. In this report we discuss their origin and their significance in terms of the Irish formula.

A. THE IRISH FORMULA

Article 76 of the (informal text of the) United Nations Draft convention on the Law of the Sea (1980) includes a number of proposed criteria for the delineation of the continental shelf of a coastal state, where its margin extends beyond 200 nautical miles from the continental baseline. One of these criteria, (para. 4(a), (i)), the so-called 'Irish formula' requires the outer limit of the shelf to be determined where the "thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such a point to the foot of the continental slope" as illustrated by Figure 1. It is, therefore, of particular importance to examine the nature, extent and origin of the dipping reflectors and to then determine whether they constitute such a sequence of sedimentary rocks. The recognition of dipping reflectors within considerable areas of unequivocal oceanic crust adjacent to an inferred continent-ocean transition, and their interpretation as sediments would make considerable differences to the size of the 'exclusive economic zones' claimed by many coastal states bordered by passive margins from application of the Irish formula.

B. PRESENT WORK

Sequences of dipping reflectors mentioned above have been studied in detail using multichannel seismic reflection profiles off the western margin of Rockall Plateau and the east coast of Greenland. Relevant data extracted from those records are presented and discussed below. Additional study has involved a comprehensive literature search and summarises the varieties of dipping reflectors described from several Atlantic passive margins. The localities studied include: the Labrador coast, the east coast of N. America, the SW and NW coasts of Africa, (Figure 2).

C. GENERAL DESCRIPTION OF THE REFLECTORS

Dipping reflectors have been recognised overlying both continental and oceanic crust (a seismic record displaying a typical dipping reflector sequence is illustrated in Figure 3, and a line drawing interpretation of the section is presented in Figure 4). Over continental crust, the reflectors lie in poorly-defined elongated basins, oriented subparallel to the inferred continental-ocean transition. In many cases, the basins are clearly bounded on their oceanward side by a shallow ridge structure, generally characterised by lack of penetration on the seismic record, which probably represents a buried basement elevation. This structure is referred to as the 'outer high', and varies in prominence from a well-defined feature, covered by a thin sedimentary sequence, and occasionally marked by a moderate topographic expression on the sea-floor, to a deeply-buried body, largely inferred from an oceanward discontinuity in the reflectors. The reflectors themselves are disposed in a weakly divergent pattern, dipping away from the main continental mass, and commonly flattening oceanward in a gentle sigmoidal form. They display a variety of depositional structures including apparent foreset patterns and clear offlap relationships with the landward continental block, (referred to in this report as the 'inner high'). In certain seismic profiles (e.g. IPOD 76-8, both migrated and unmigrated), the extreme oceanward sections of the reflectors can be seen to describe a gentle upturn against the buried 'outer high' suggesting an onlap unconformity. In most profiles, however, reflectors maintain a constant dip oceanwards and can be traced to a considerable depth.

At the top of the dipping sequence lies a subhorizontal, generally smooth prominent reflector. It is commonly observed over much of the subcrop of the dipping reflectors, although typically becomes discontinuous and untraceable onto the 'inner high'. Oceanwards the reflector can in some cases be followed with difficulty across the 'outer high' into horizontal units immediately overlying the ocean crust.

Further sequences of dipping reflectors are observed within the area occupied by oceanic crust immediately adjacent to the continent-ocean transition, the site of which approximates to the line of the 'outer high' feature. In the example illustrated in Figures 3 and 4 oceanic crust is confirmed by the presence of magnetic anomalies resulting from early Tertiary sea-floor spreading (Roberts et al., 1979), although a 'rough' acoustic basement typical of many areas of oceanic crust is not necessarily present. The dipping sequences oceanwards of the 'outer high' are broadly similar to those described overlying continental crust, in that they dip oceanwards, but may differ markedly in three respects, each of which is evident in the Rockall examples.

(a) The reflectors are generally weak and discontinuous and can only be recognised in the uppermost levels of the 'basement', lying beneath horizontal sediments.

(b) In general the reflectors maintain a constant dip, exhibiting neither the structures suggestive of a prograding sequence displayed by those overlying continental crust, nor a clear stratigraphic relationship to the oceanward face of the 'outer high'.

(c) The reflectors can nowhere be traced deeper than 5-6km and terminate upward against a strong reflector which is tentatively suggested to be the upper surface of the oceanic basement and must therefore be diachronous. The origin of this strong reflector and its chronostratigraphic relationship to the prominent reflector observed overlying supracontinental dipping reflectors is purely speculative. However, the age obtained by the DSDP for the top of the dipping reflector sequence at sites 403 and 404 pre-dates the upper Palaeocene age of the youngest oceanic magnetic anomaly (24B) identified west of Rockall Plateau (Shipboard Scientific Party, 1979).

By contrast to Rockall, in the Greenland examples (Figure 5), the reflectors maintain a shallowly-dipping aspect for considerable distances over oceanic crust identified by "sea floor spreading" type anomalies, the oldest of which is of late Palaeocene age (anomaly 24, after La Brecque, 1977). The dipping reflectors are locally observed in crust of anomaly 20 age (middle Eocene) lying as much as 100 km from the interpreted continent-ocean boundary. Their relationship with the ubiquitous, smooth prominent reflector remains as equivocal as the Rockall examples. Minor variations in dip of the reflectors locally present a gently undulating pattern which is provisionally interpreted as cross-cutting, channelling or deposition along strike.

D. COMPOSITION OF THE REFLECTORS

No direct sampling of the dipping reflectors has been possible by drilling, although an attempt was made during Leg 48 of the DSDP to penetrate the sequence at Sites 403 and 404 (Shipboard Scientific Party, 1979). The oldest sediments recovered were a tuffaceous sandstone and conglomerate of early Eocene to late Palaeocene age, from depths of 489 and 389m respectively, of which the latter was (provisionally) correlated by use of well logs to the level of the prominent reflector discussed above. A dredge haul was made by Watts et al. (1975) off the north Hatton Bank in an area where seismic profiles indicate outcrop of the upper horizons of the dipping sequence. The haul recovered arenaceous arkoses and rudaceous material of late Cretaceous to early Tertiary age. Compressional wave velocity tests on the samples yielded velocities of 4.0 to 5.6 km/s at 0.1 kbar confining pressure. These figures are compatible with both interval velocities recorded for the dipping reflector sequences at depth from IPOD lines 76-5, 7 and 8 which fall within the range of 3.5 and 4.6 m/s, and apparent velocities obtained from the 76-5 refraction line between 4.2 and 5.0 m/s (P.R. Miles, pers. comm.). Although a direct correlation of these samples with the main body of the reflectors must be tentative, it may be inferred from these data and the IPOD Leg 48 results that these shallow-water, coarse proximal deposits contribute a significant clastic/volcanoclastic amount of material to the sequence. High seismic refraction velocities have also been reported for sediments located at shallow levels in the crust by Elverhoi & Gronlie (1981) in the northern and western Barents Sea.

The presence of extrusive volcanics, however, cannot be excluded, and available data indicate that the overall composition of the sequence may vary considerably between localities.

A wholly basaltic composition for the deep reflectors has been alternatively proposed by Talwani (pers. comm.) and Smythe (1980), who interpret the reflectors as a layered seris of lavas, formed by Icelandic-type flow. Smythe considers that their dip steepens with depth, and by the way of an inferred downward flexure they pass into a zone of subvertical dykes, orientated parallel to the continental margin. The intrusions/lavas thus embrace the zone between unequivocal oceanic and continental crusts but are here inferred to be of oceanic origin. Smythe considers that the refraction velocities obtained can be alternatively interpreted as indicating the presence of basic intrusive and extrusive sequences. Talwani, however, whilst interpreting sequences of dipping reflectors observed on the northwestern scarp face of the Voring Plateua as basaltic in composition, infers that they are lava flows throughout, and lateral extensions of the more typical oceanic crust of the Lofoten Basin. He maintains that the early Tertiary magnetic anomaly (24B) which he has identified over the northwestern edge of the plateau confirms the oceanic (and thus predominantly basaltic) nature of the suprabasement material. The implications of the interpretations of both of these workers for the definition of the legal continental 'shelf' however, (sensu article 76, of the LOS draft, are considerable and are discussed below.

E. MODELS OF FORMATION OF THE REFLECTOR SEQUENCE

1. A common characteristic of the early phases of rifting is the development of graben and half-graben, typically accompanied by listric faulting which results in rotated basement blocks. It is likely that during such a period of regional uplift and crustal attenuation prior to separation, erosion would be extremely rapid, supplying large amounts of sediment and may also be accompanied by extrusion. Contemporaneous accumulation of the eroded material in deepening graben structures is envisaged, at the high deposition rates of the order of those estimated for shallow water marine sedimentation at sites 403 and 404 (at least 71.0 m/my, Shipboard Scientific Party, 1979). Volcanic extrusions, possibly related to the rift system near to the incipient ridge axis may

contribute significant amount of material to the basin fill. This supply of material combined with the rapid and persistent progradation of a fan or outwash deposit from the eroded 'inner high' source area could develop a profile identical to those observed through the dipping reflector sequences (Figure 6A).

The nature and composition of the prominent reflector is uncertain. In normal progradational sedimentary sequences (Figure 7) the upper surface of each sequence is composed of a horizontal diachronous series of topsets, each of which dips at its leading edge into a series of advancing foresets. It is possible that the prominent reflectors at the top of the dipping sequences described above for Figures 3, 4 and 5 correlate to such an horizon. Between the inner and outer 'highs' the relationship of this prominent reflector to the dipping sequence is equivocal and from the seismic data available it is uncertain whether the relationship is that of a sharp angular erosional unconformity (Figure 7B) or that of a normal diachronous topset (Figure 7A). It is possible that each interpretation may be correct in different parts of a profile.

The dipping reflectors observed within the oceanic crust are likely to be of a markedly different character, in particular of a less continuous nature than those described above. A particular contrast is their disposition beneath a reflector which is traced oceanwards without break into unequivocal oceanic crust. The inference of this observation is that the reflectors represent a structural feature within the basement. The oceanic basement is composed largely of both extrusive and intrusive material, but may include significant proportions of volcanoclastic and other sedimentary deposits, and it is these which may contribute to the 'intrabasement' reflectors. It is envisaged that this model may be particularly applicable to the Rockall sections, as indicated above. As inferred in the following section, similar reflectors may be within oceanic crust at the base of the Greenland dipping sequence but are unresolved on present multichannel seismic records.

2. A model involving a similar process of a rapidly prograding sedimentary sequence is illustrated in Figure 6C. It is here envisaged that the two areas of dipping reflector described above, i.e. those overlying continental crust, and those observed in crust characterised by oceanic type magnetic anomalies, may be more closely related genetically and chronologically than suggested by Model (1).

A prograding sequence extending from a continental mass would continue outwards over the newly-formed oceanic floor if unchecked by a topographic feature (such as an outer high). Provided that the necessary sediment supply continued, a laterally extensive sequence of dipping foresets could develop. These would post-date the formation of oceanic crust and present a strongly diachronous upper surface onto which more typical marine sediments would be deposited.

Minor fluctuations in the dip of the reflectors may be evidence of shallow basement highs, against which poorly-defined, offlapping sequences can be recognised. Although the variations are too small to examine quantitatively, the overall pattern is tentatively interpreted as indicating the presence of buried channels and sediment transport along strike.

3. The third model for the dipping reflector sequences is that proposed by Smythe (1980). He suggests that the reflectors may represent a layered series of basaltic lava sheets at their continental end, which can be traced laterally oceanward into a suite of dykes and sills of similar composition at depth (Figure 6B). Since such lava sheets would need to have been initially supplied from an oceanward source, subsequent tilting and subsidence of the margin would have been necessary to produce their present attitude. The nature of the outer high remains uncertain, although it must be by inference also composed of intrusive and of extrusive material. Over oceanic crust this hypothesis is apparently supported by the occurrence of intrabasement reflectors but is strongly contradicted over continental crust by the observation of inter-formational sedimentary-type structures, and the shallow basinal form to the dipping sequences, occasionally observed between inner and outer 'highs'. Furthermore, it is perhaps unlikely that sufficient penetration of this (~4km) basaltic sequences on the seismic record would be obtained to identify the deepest dipping reflectors which are recognised on numerous profiles. Indeed, the acoustic aspect of inferred lava sheets elsewhere in the Rockall area (Roberts et al., 1981 and unpublished data from deep drill hole [pers. comm., BNOC, 1981]) is markedly different from that of the dipping reflectors described here. The recent advances made in techniques of data acquisition and processing enable the recording of up to 5km thickness of dipping reflectors (at 9km total depth of section) (Fig. 3, 4), but do not afford seismic penetration to the base of the sequence. It is believed that the data to be collected from the present

field work in the area of the dipping reflectors (IPOD Survey, 1981) will be of use in elucidating the problem further.

In summary, it appears that models (1) and (2) provide more likely interpretations of the bulk of the available data related to the dipping reflectors than model (3). We consider that many of the structures in the seismic record, e.g. the offlapping relationships, the basinal form, and the intraformational unconformities, are best interpreted as a sedimentary sequence containing significant amounts of extrusive material. It is interesting to note that whilst a similar sedimentary composition is envisaged for the dipping reflectors in models (1) and (2) immediately adjacent to the continental mass, it appears that the sequences observed off Rockall and E. Greenland may have different origins. This could be interpreted to indicate a greater or more persistent supply of sediment from the E. Greenland continent, and does not rule out the possibility that undetected intrabasement reflectors may exist at depth below the shallowly dipping prograding sedimentary cover, as indicated in Figure 6C. It therefore remains to assess the extent to which these sedimentary sequences may affect present interpretations of the Irish Formula.

F. CONCLUSION: APPLICATION TO THE IRISH FORMULA

Figures 8a, b and c show the hypothetical positions of the outer edges of the continental margin as defined by the Irish Formula. The figures are largely self-explanatory and the relevant points only are discussed below.

Figure 8a. The thickness of sedimentary rock decreases rapidly oceanward onto the 'outer high', and the limit of the continental margin according to the Irish formula approximates to this feature. The dipping reflectors oceanward of the outer high are interpreted as of a mixed composition which, despite the probability of their containing significant amounts of sedimentary and volcanoclastic material, are probably dominated by oceanic extrusive material.

Figure 8c. The increased extent of the sedimentary rocks by their progradation to the oceanic crust widens the distance between the inner high and the (outer) line of the continental margin considerably where no significant 'outer high' feature is present, such as in the example of E. Greenland.

Figure 8b. The application of the Irish formula to model (3) where the reflectors represent a non-sedimentary sequence requires the positioning of the outer edge of the continental margin in relation to the thin cover of post-rift sediments. The consequence is a substantial decrease in width between the 'inner high' and the line of continental margin. Using the example of continental margin west of Rockall, the reduction would be in the order of 65%, whereas off the coast of E. Greenland, the decrease in width could be greater than 85%.

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FIGURE CAPTIONS

Figure 1. Application of Irish formula to simple sediment cover - undifferentiated basement model at the continent-ocean transition.

Figure 2. Locations of dipping reflectors in the North Atlantic as recorded in published and unpublished literature. Letters refer to sources: A, Eldholm & Sundvor 1980; B, Talwani & Udintsev 1976; C, Unpublished IPOD data of Leg 48 1976; D, Unpublished commercial multichannel lines 1977; E, Unpublished multichannel lines 1974; F, Unpublished commercial multichannel lines 1977; G, Grant 1975; H, Klitgord & Grow 1980; I, Gerard 1981. Locations of Figs 3, 4 and 5 indicated.

Figure 3a, b, c Seismic profile RH116, traversing the continental margin west of Rockall. Section illustrates: dipping reflector sequences; smooth, prominent reflector; inner and outer highs; typical oceanic and continental basements. Point A on Fig. 3b indicates position of deepest identifiable dipping horizon.

Figure 4. Line drawing of Figure 3 indicating the attitude of the dipping reflectors and their relationship to the prominent reflector.

Figure 5. Line drawing of seismic line 307 across the E. Greenland margin illustrating greater lateral development of the dipping reflector sequence.

Figure 6. Models used in the alternative interpretations of the dipping reflector problem.

A. An accumulation of dipping reflectors as progradational sequences composed of both sediment and extrusive material in basins floored and bounded by continental crust.

B. The dipping reflectors represent the upper part of a downward flexing series of extrusives and intrusives which form part of an early oceanic or transitional crust.

C. Indicates the continuation of prograding dipping reflector sequence beyond the continent-ocean transition.

Figure 7. A. Schematic model of prograding sequence of sedimentary units. Topset (ts), foreset (fs) and bottomset (bs) features indicated. Note upper surface is strongly diachronous, and could represent prominent reflector (pr) discussed in text.

B. Alternative interpretation of junction between dipping reflectors and prominent reflector (pr) as an erosional unconformity. For discussion, see text.

Figure 8. Positions of continental margins as defined by the Irish formula for Models 1, 2 and 3.

Fig. 1

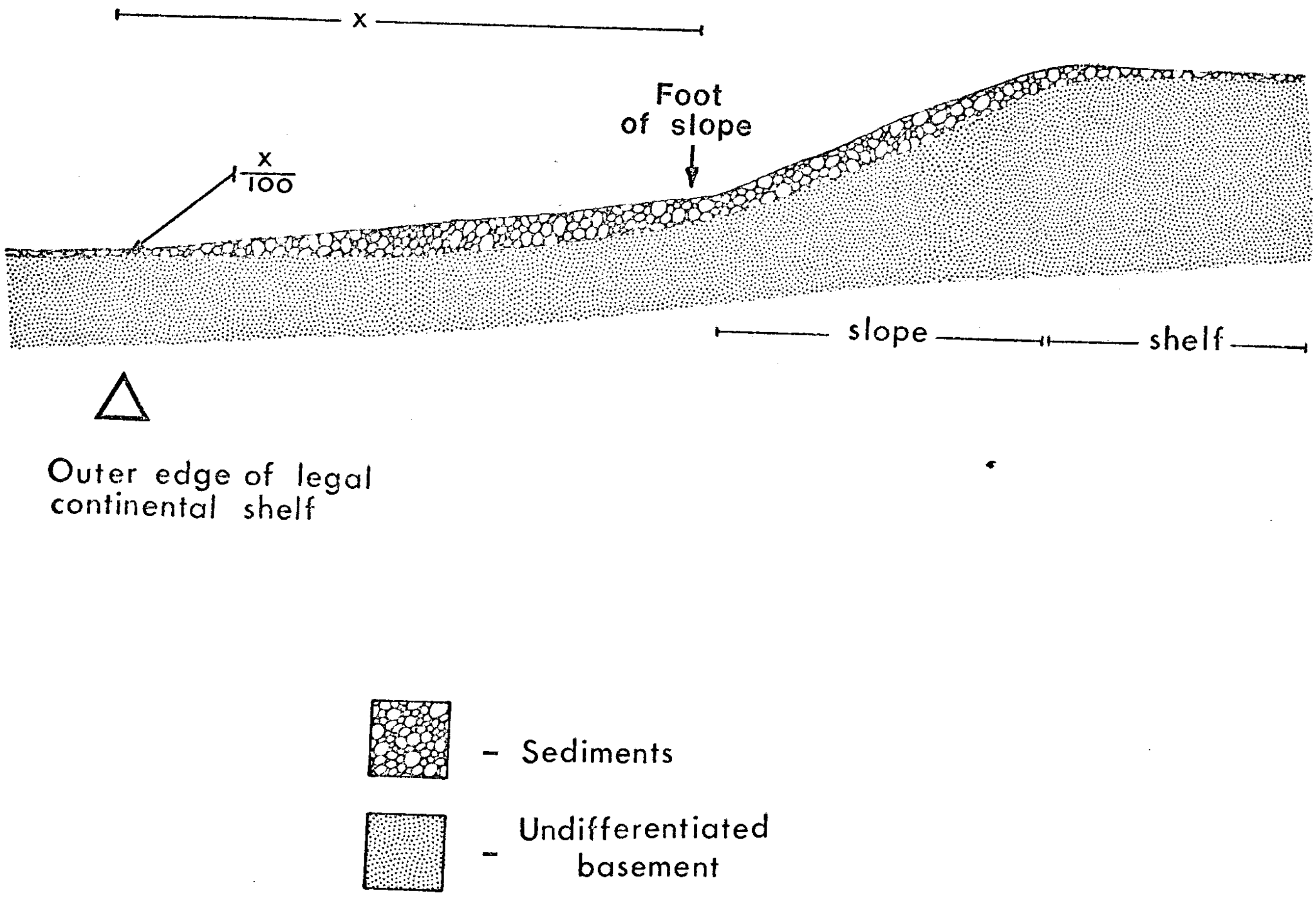

x
Foot
of slope
x
100
slope
shelf
Outer edge of legal
continental shelf
- Sediments
- Undifferentiated
basement

Fig. 2

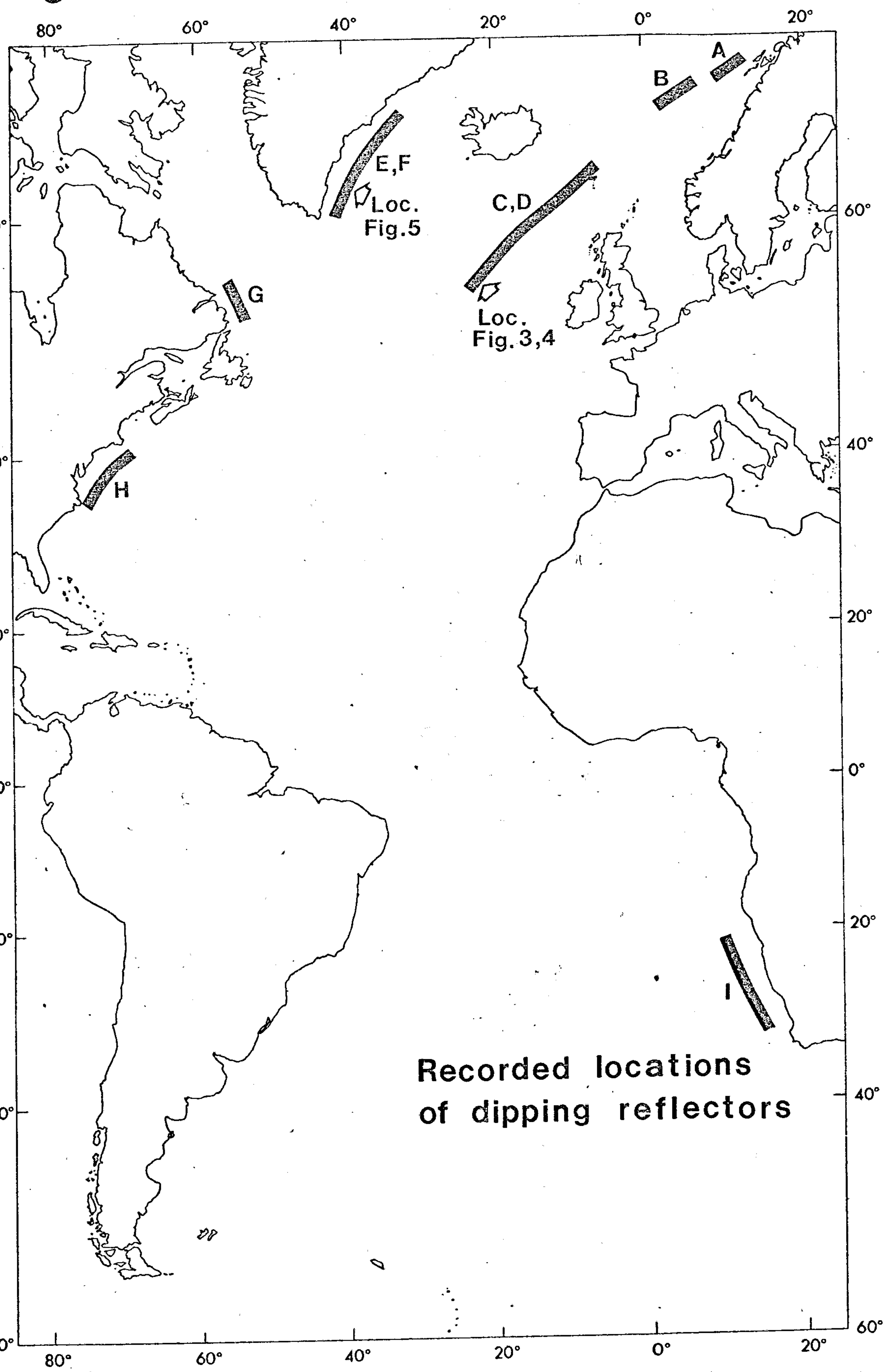

80°
60°
40°
20°
0°
20°
A
B
E,F
Loc.
Fig.5
C,D
Loc.
Fig. 3,4
G
H
I
60°
40°
20°
0°
20°
40°
60°
Recorded locations
of dipping reflectors

Fig.3 WEST ROCKALL

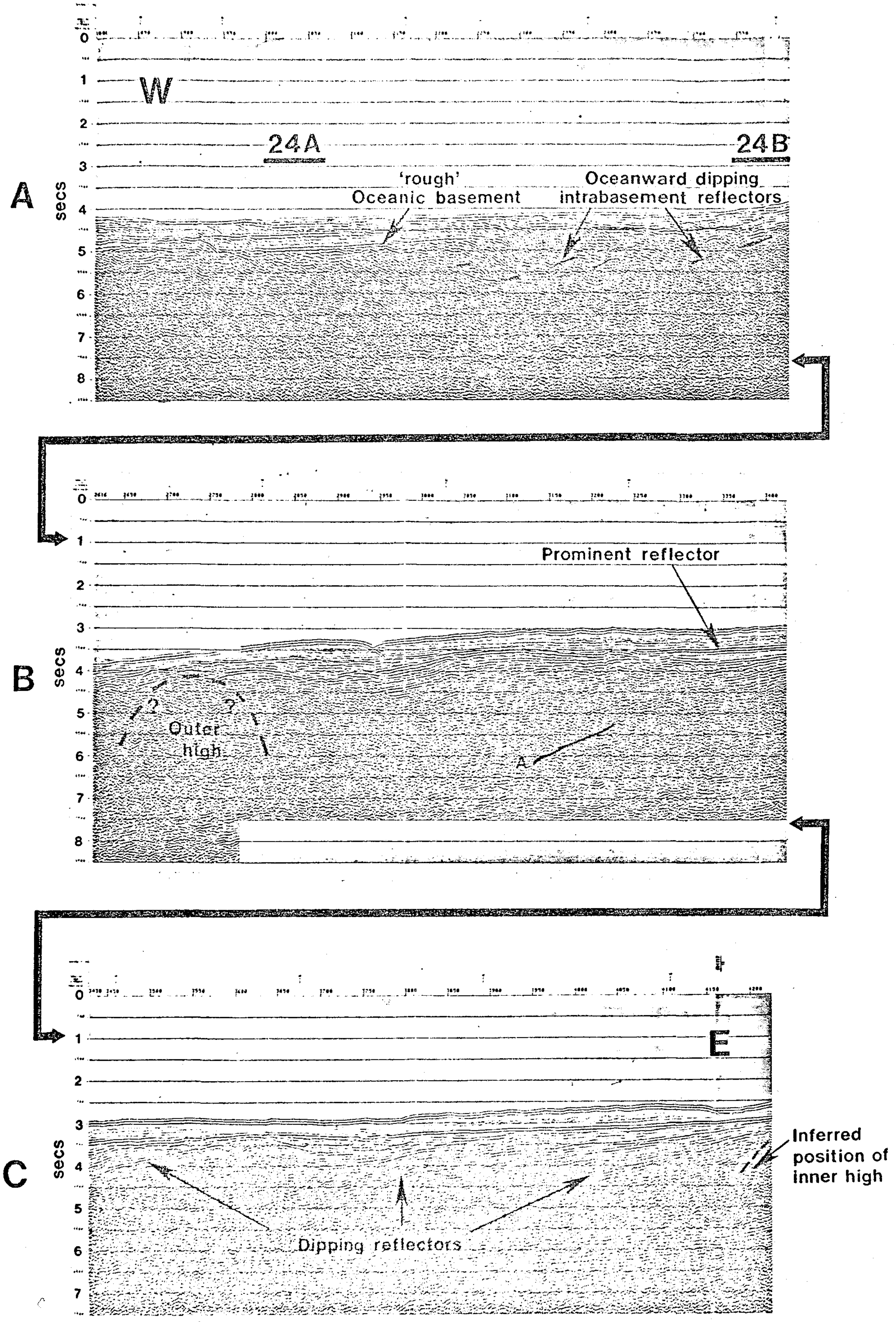


Fig.4 LINE RH116 WEST ROCKALL

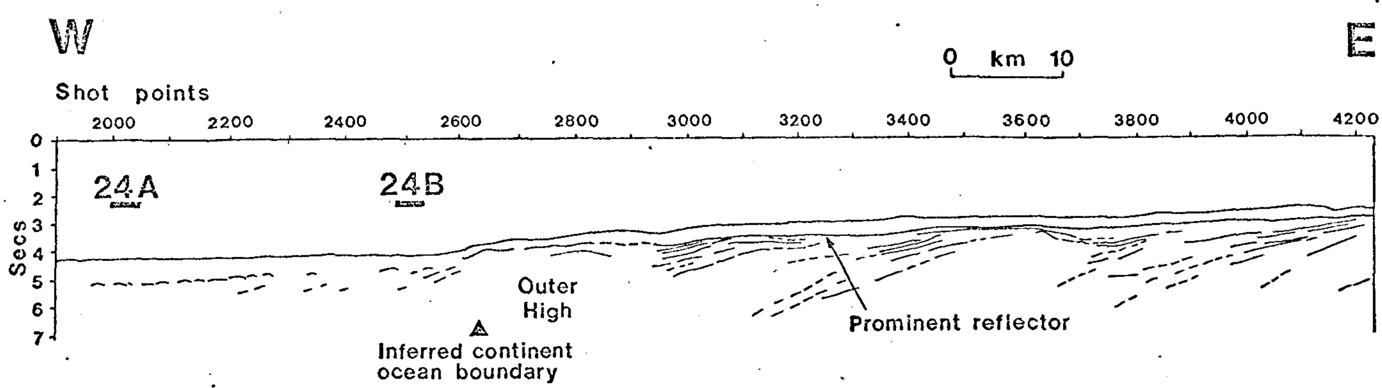


Fig.5 LINE 307 EAST GREENLAND

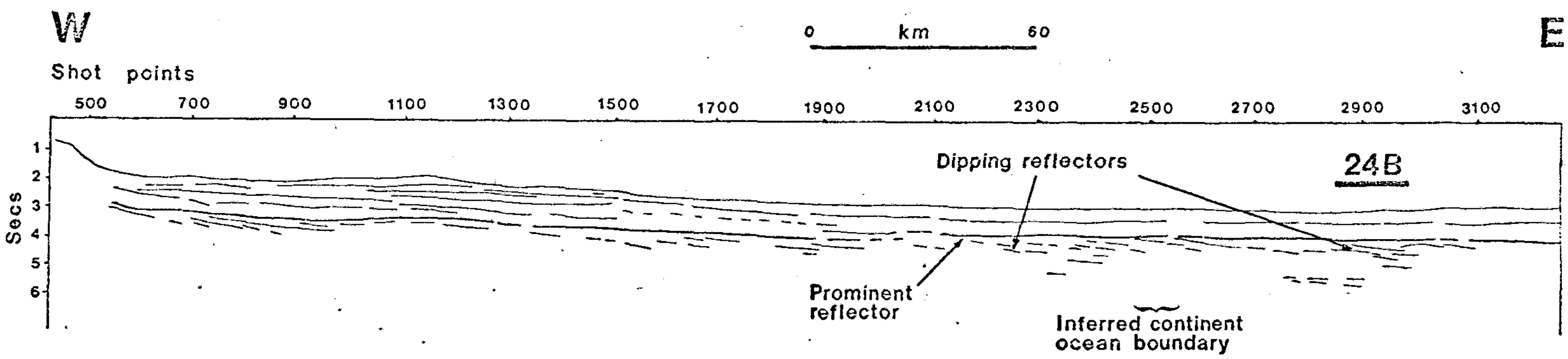


Fig. 6

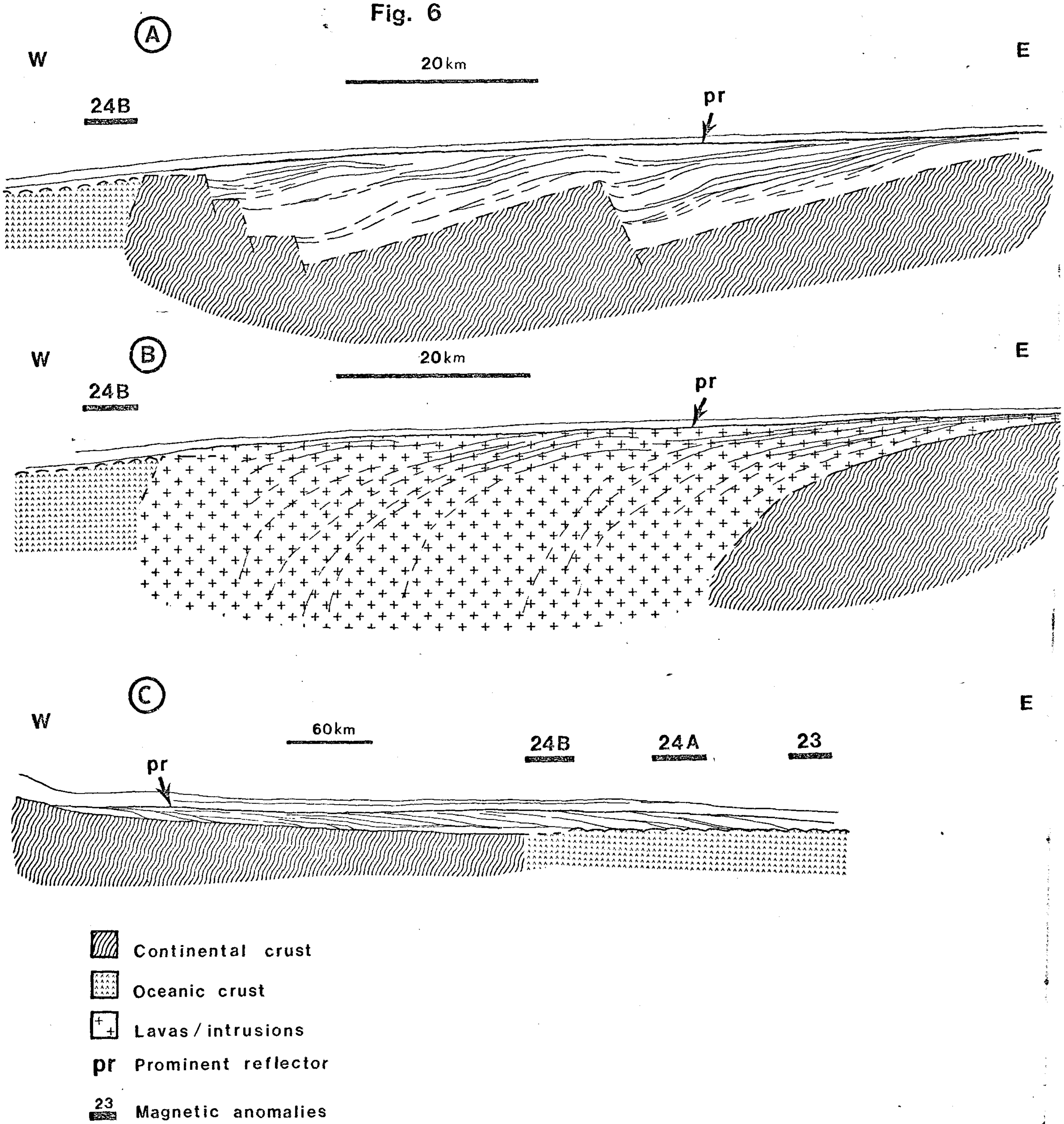

A
W
E
20km
24B
pr
B
W
E
20km
24B
pr
C
W
E
60km
24B
24A
23
pr
Continental crust
Oceanic crust
Lavas / intrusions
pr Prominent reflector
23 Magnetic anomalies

Fig. 7a

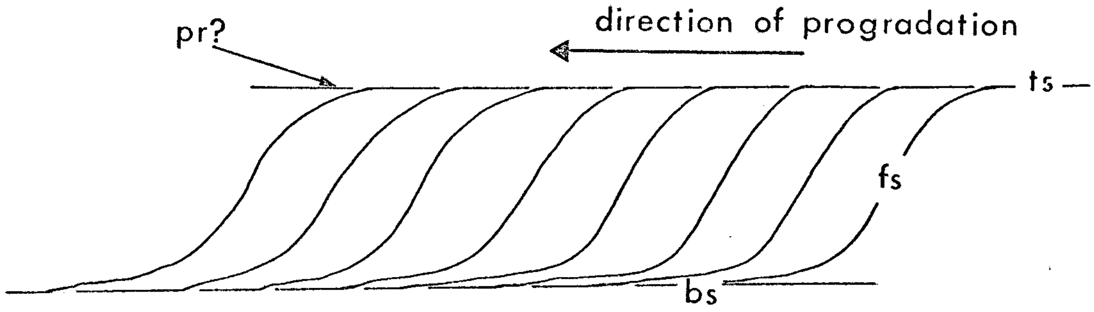


Fig. 7b

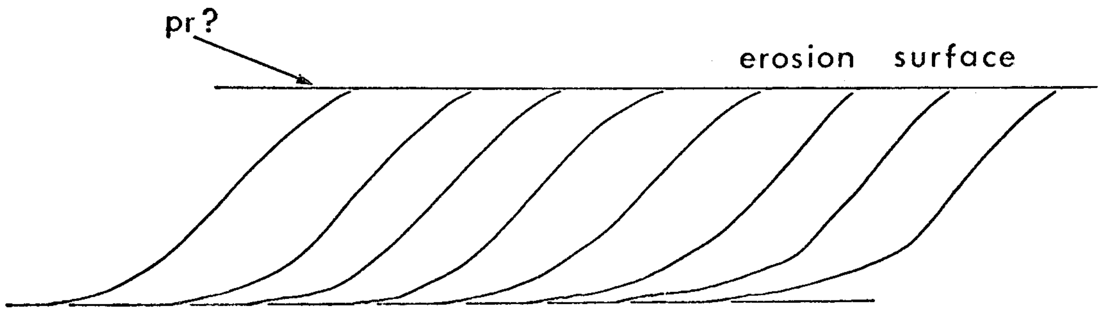
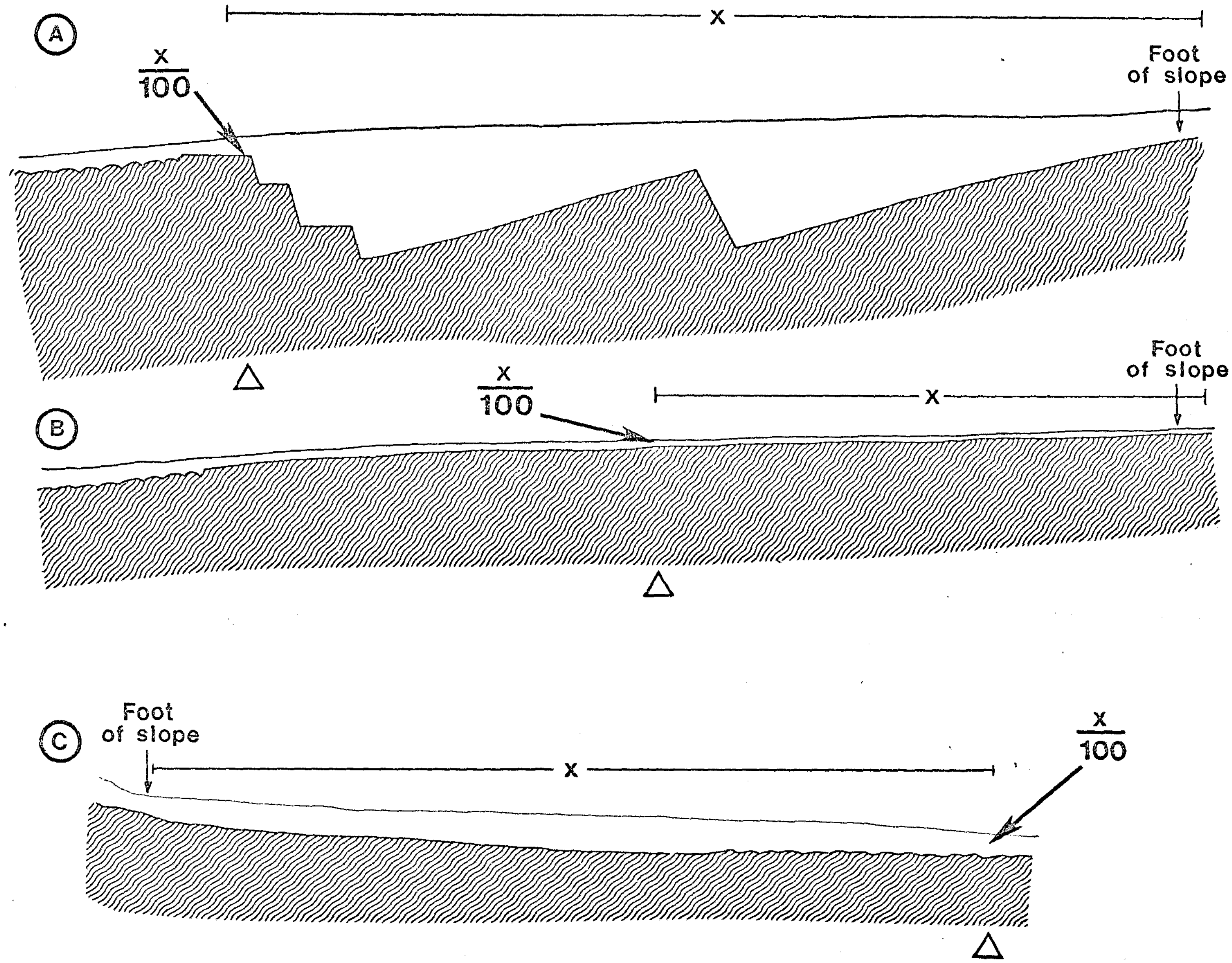


Fig. 8



△ - Outer edge of legal continental shelf