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MAJOR CRUSTAL FEATURES DISCLOSED BY THE ECORS DEEP SEISMIC PROFILES

by

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(15 figures)

ABSTRACT.- The ECORS project was launched in 1983 with the aim of studying France's main geological features by deep seismic profiling of the crust. The ECORS profiles have been located on structures of major significance : outer zone of the Variscan orogenic belt, Mesozoic basins in the English Channel and the Bay of Biscay and recent orogenic belts (Pyrenees and Alps). A special effort was made to improve deep reflections through the use of powerful seismic sources, long recording spreads and large CDP coverage. The seismic reflection surveys have also been complemented wherever possible by additional geophysical measurements (magnetism, gravity, MT, wide-angle and refraction seismic) and geological surveys. The ECORS profiles have contributed to outline the areal framework of the crustal structure within a large region in France and adjacent areas. They also shed new light on major geodynamic phenomena such as variations in the Variscan frontal detachment, the lower crust's formation, genesis of the cratonic basins and crust-mantle relationships beneath the recent fold belts.

RESUME.- Le programme ECORS a été lancé en 1983 dans le but d'étudier les principales structures géologiques de France par des profils de sismique profonde à travers la croûte. Les profils ECORS ont été implantés sur les structures les plus significatives : la zone externe de l'orogène hercynien, des bassins mésozoïques en Manche et dans le Golfe de Gascogne et des chaînes orogéniques récentes (Pyrénées et Alpes). Un effort particulier a été fait pour améliorer les réflexions profondes en utilisant des sources sismiques puissantes, de longs dispositifs d'enregistrement et une couverture multiple importante. Les campagnes de sismique reflexion ont été complétées dans la mesure du possible par d'autres mesures géophysiques (magnétisme, gravimétrie, MT, sismique grand angle et réfraction) et des observations géologiques. Les profils ECORS ont contribué à définir la structure de la croûte à l'échelle d'une vaste région en France et dans les zones adjacentes. Ils ont également jeté une lumière nouvelle sur des phénomènes géodynamiques importants comme les variations dans la forme du détachement frontal hercynien, la formation de la croûte inférieure, la genèse des bassins cratoniques et les relations entre la croûte et le manteau sous les chaînes plissées récentes.

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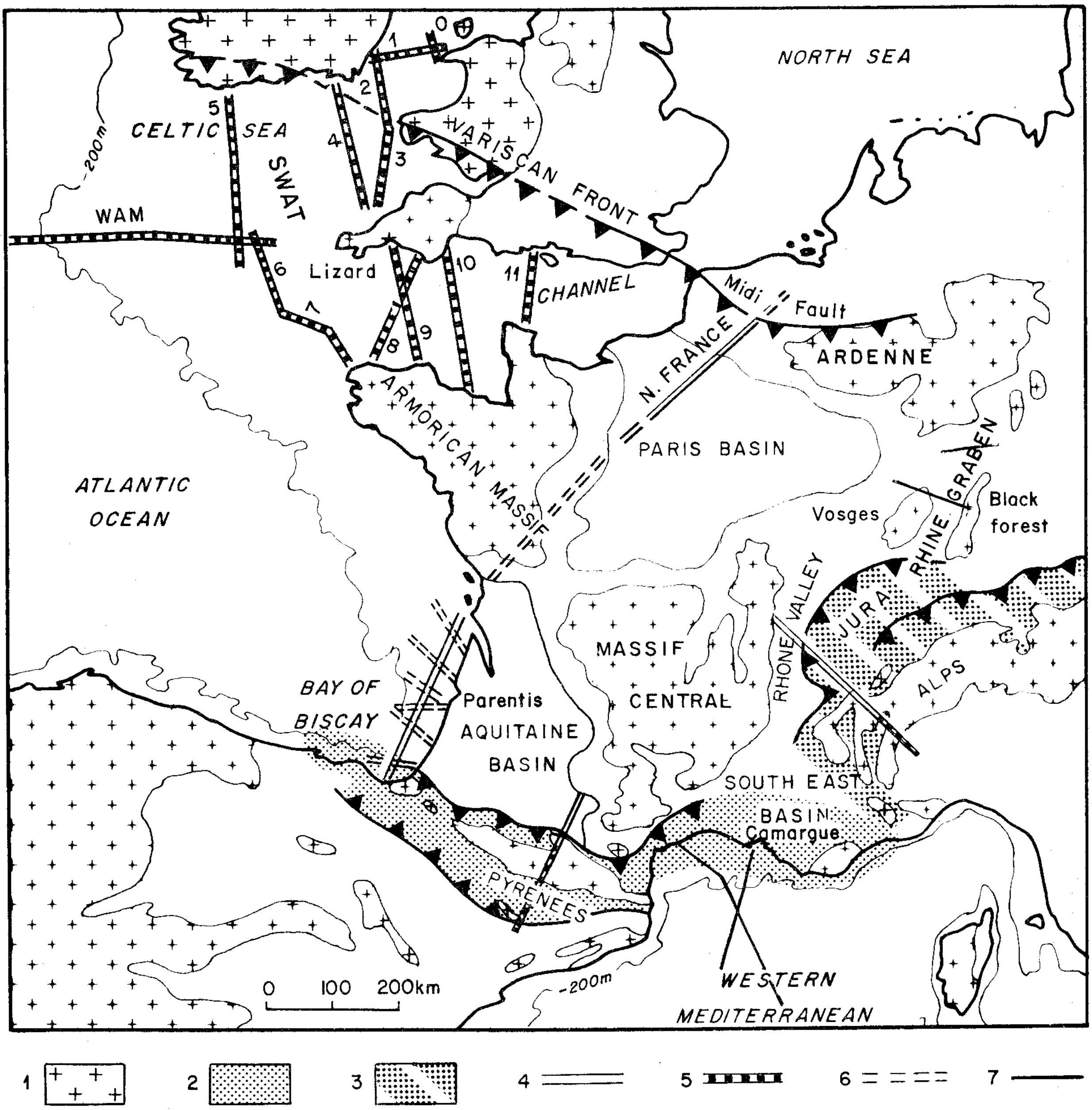


Figure 1.- Main geological features in France and location of the ECORS profiles completed and planned.
(1) Palaeozoic outcrops, (2) Pyrenean range, (3) Alpine range, (4) ECORS near-vertical seismic reflection profile, (5) International cooperation profile, (6) ECORS wide-angle seismic reflection and refraction, (7) planned profile.

INTRODUCTION : THE ECORS OPERATIONS

The ECORS project was launched in 1983 with the goal of investigating France's main geological features by deep seismic profiling of the crust. The project is jointly managed by the Institut Français du Pétrole, the Institut National des Sciences de l'Univers (formerly INAG)/ and Elf-Aquitaine. The Institut Français pour la Recherche et l'Exploitation de la Mer (formerly CNEXO) is also a partner for offshore operations.

France offers interesting opportunities for studying the structure of the continental crust in various geological settings (Bois & Allegre, 1983). the present basement in France was consolidated by the Variscan orogeny (400-300 Ma). Older terranes such as the Mancellia, Central Armorican and Aquitaine (?) blocks have however been identified within this fold belt (Autran *et al.,* 1980; Chiron, 1980; Ziegler, 1986) (Figs 1 and 9). Since the early Mesozoic, the Variscan basement has been subjected to subsidence within three large cratonic basins, Paris, Aquitaine and Southeast, while the margins of the Alpine Tethys and Atlantic Oceans were formed. In the Tertiary, the Alpine Tethys Ocean was closed and the Alps and Pyrenees, two major fold belts, were formed in

Area Profile length	Geophysical operations	Years	Operator	Participation
Northern France 228km	Reflection Wide-angle & refraction MT Airmag	1983-84 1983-84-85 1984 1985	ECORS	FSH
SWAT Western Channel and Celtic Sea 1600km	Reflection	1983	BIRPS	ECORS ELF(UK)
Bay of Biscay 295km	Reflection ESP	1984	ECORS	FSH HISPANOIL
Rhine graben	Wide-angle (test)	1984	ECORS-DEKORP (Germany)	
WAM Celtic Sea Western Approaches Margin - 645km	Reflection	1985	BIRPS	ECORS ELF(UK)
Pyrenees – French leg 130km	Reflection offset shooting gravity	1985	ECORS	Spanish Group ESSOREP
Pyrenees – Spanish leg 140km	Reflection	1986	Spanish Group	ECORS ESSOREP
Alps – Whole area	Wide-angle and Refraction	1985	ECORS-CROP	BP
Alps – French leg 130km	Reflection	1986	ECORS	CROP(Italy) BP EURAFREP
Alps – Italian leg 70km	Reflection	1986	CROP(Italy)	ECORS

Figure 2.- ECORS geophysical operations (modified from Bois *et al.*, 1987).
Profile length of the main near-vertical seismic reflection profiles. FSH: funding by the French Ministry for Industry. BP, Elf (UK), ESSOREP, EURAFREP, HISPANOIL: oil companies.

	N.France	Pyrenees (French segment)	Alps (French segment)	Biscay	SWAT
VIBRATOR SOURCE					
Vibrators	5x13.5 t	4x13.5 t 2x7 t	5x13.5 t		
Sweep	8-38 Hz	10-40 Hz	9-39 Hz		
Length	20s	60s	50s		
V.P. Interval	80m	40m	80m		
Coverage	9600%	12000%	6000%		
EXPLOSIVE SOURCE					
Charge		20kg			
S.P. Interval		240-480m			
Coverage		2000%			
AIR GUN SOURCE					
Capacity				8536 cu.in.	5560 cu.in.
pop Interval				50m	50m
Coverage				30+24	30
RECORDING					
Traces	192	240	120	120+96	60
tr. Interval	80m	40m	80m	25m	50m
Spread	Symmetrical	Symmetrical	Asymmetrical	2 Stream. @ 7.5km	Streamer
Length	32s	75s	64s	15-16s	15s
Sampling	4ms	4ms	4ms	4ms	4ms

Figure 3
ECORS and BIRPS-ECORS operations: main fields parameters.

the southern and southeastern parts of the country as the result of collision between Europe, Africa and smaller intervening blocks. In the meantime, large rifts were formed in the eastern part of the country and the western Mediterranean margin was rifted (Oligocene).

The first ECORS profile was completed in northern France across the northern part of the Variscan fold belt. Other profiles have been carried out in the Bay of Biscay, the Alps and the Pyrenees, thanks to international cooperation (Bois *et al.*, 1987) (Fig. 2). In the meantime, the ECORS group participated in the SWAT and WAM projects operated by the BIRPS group in the English Channel and the Celtic Sea. Operations have resumed on the Alps profile and a marine survey will also be carried out soon in the Gulf of Lions.

During the ECORS operations, a special effort was made to improve the deep reflections. Vibrators had to be used in northern France, the Alps and part of the Pyrenees profiles for environmental reasons. This source was generally composed of five heavy vibrators with a 8-40 Hz sweep, achieving a 60-120 fold coverage. On these profiles, explosive blasts were also shot with longitudinal and lateral offsets in order to obtain both refraction and deep reflection markers. Explosive sources were fortunately used in most of the Pyrenees profile. The 20-60 fold coverage provided excellent results. The recording spreads were composed of 120-240 traces.

An 8536 cu.in. air gun array, with very high energy in the 7-60 Hz frequency range, was used in the Bay of Biscay. A 30 fold coverage was achieved with a 3000 m streamer. A second ship 7.5 km behind the first also recorded the shots with a 2400 m streamer. The continuity and energy of the deep reflections were appreciably enhanced by the offset recording both onshore and offshore.

Wide-angle and refraction surveys were carried out in northern France, the Bay of Biscay and the Alps in order to get some information on the crustal velocities. Wide-angle reflection from fan shooting recorded by low-frequency self-recording stations was performed to profile the Moho in preliminary surveys, to extend the results of the near-vertical reflection surveys, and to complete the results of these surveys where they failed to show deep crustal reflections (Hirn *et al.*, 1987).

Likewise, interpretation was greatly helped by magnetotelluric stations in northern France. Additional gravity and magnetic surveys were carried out wherever the available data were insufficient.

The purpose of this paper is to review the main crustal features thus far observed on the ECORS profiles. These profiles will be presented from north to south following the course of the geological history.

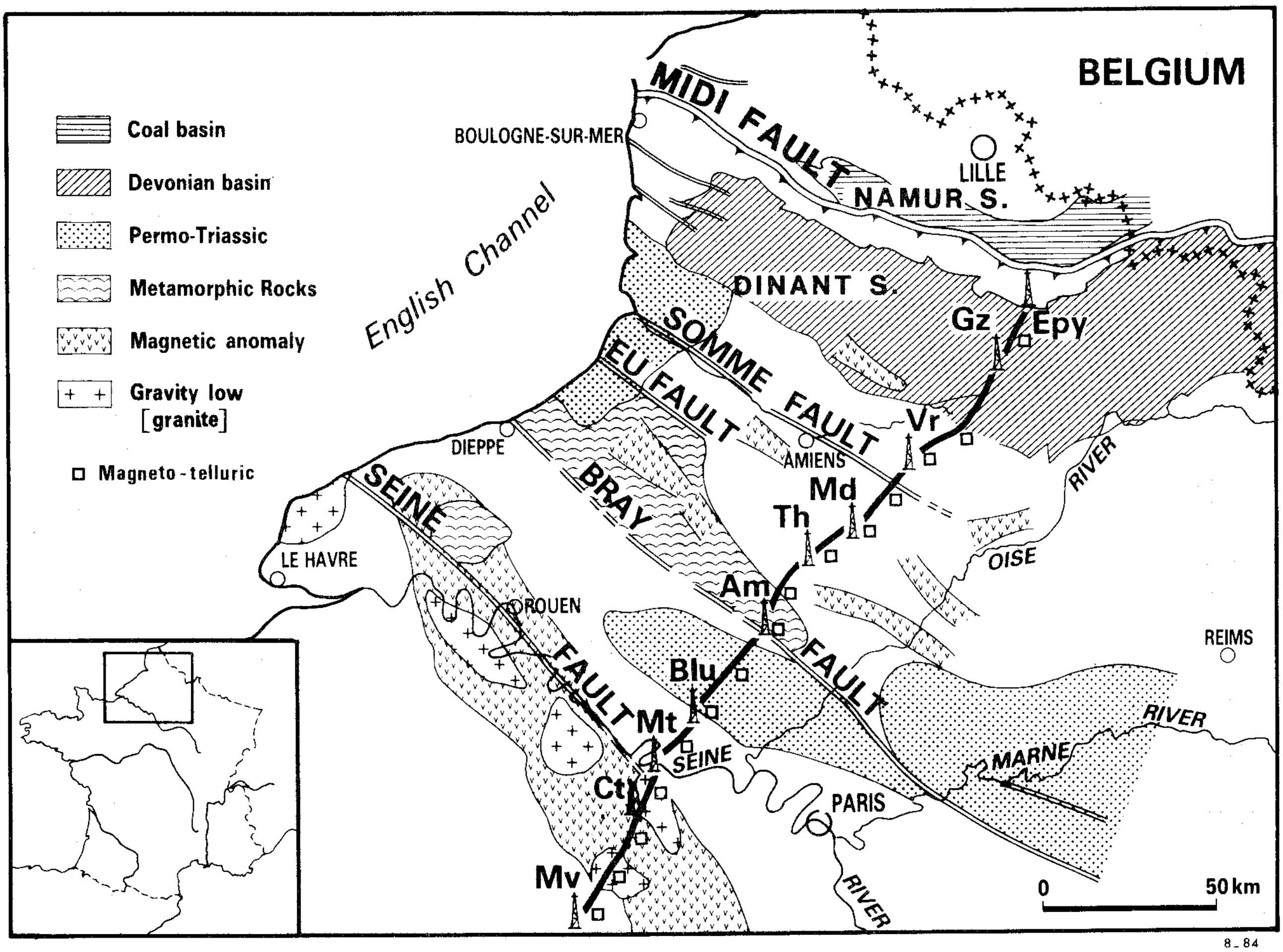


Figure 4.- Pre-Jurassic subcrop and outcrop in northern France and location of the ECORS northern France profile. Abbreviations Mr, Ct, Epy indicate wells drilled down to the Palaeozoic basement (modified from Cazes *et al.,* 1985).

THE NORTHERN FRANCE PROFILE

The first ECORS profile, 230 km long, was aimed at studying the Variscan fold belt lying below the Mesozoic and Tertiary cover of the Paris basin although a few Devonian and Carboniferous outcrops can be observed to the west (Boulogne) and to the east (Ardenne) of the profile (Cazes *et al.,* 1985; Bois *et al.,* 1986) (Fig. 4).

The fold belt is bound in the north by the Midi fault, a major thrust system which extends laterally from Germany to southern Britain (Fig. 1). It is a low-angle thrust that forms the southern boundary of a large foredeep coal basin, the Namur synclinorium, which is very well documented (Bouroz *et al.,* 1961). South of the Midi fault, the Paleozoic outcrop and subcrop delineate the Dinant synclinorium made up of a thick Devonian to Carboniferous series including small amounts of Silurian and Cambrian rocks. This unit was folded and thrust along the Midi fault and over the Brabant foreland overlain by thinner Devonian to early Carboniferous platform sediments and the late Carboniferous molasse foredeep. Thin-skinned tectonics had been demonstrated in this area by mining operations, previous seismic surveys and wells, and even by field mapping in the eastern outcrops (Raoult & Meilliez, 1986). The northwards displacement of the Dinant nappe was assumed to extend over several tens of kilometers before the northern France profile was completed. One of the main objectives of this survey was to trace the base of this nappe down into the deep crust.

The entire region is crossed by several northwest trending lineaments controlling the pattern of the rivers. These lineaments are assumed to correspond to late Variscan strike-slip faults (Arthaud & Matte, 1977) that were reactivated during the Mesozoic and Tertiary tectonic events. The main one, the Bray fault, is associated with a major surface anticline formed during the Eocene compression.

Many gravity and magnetic anomalies occur in this part of the basin. A large magnetic anomaly extends over 400 km southwards across the

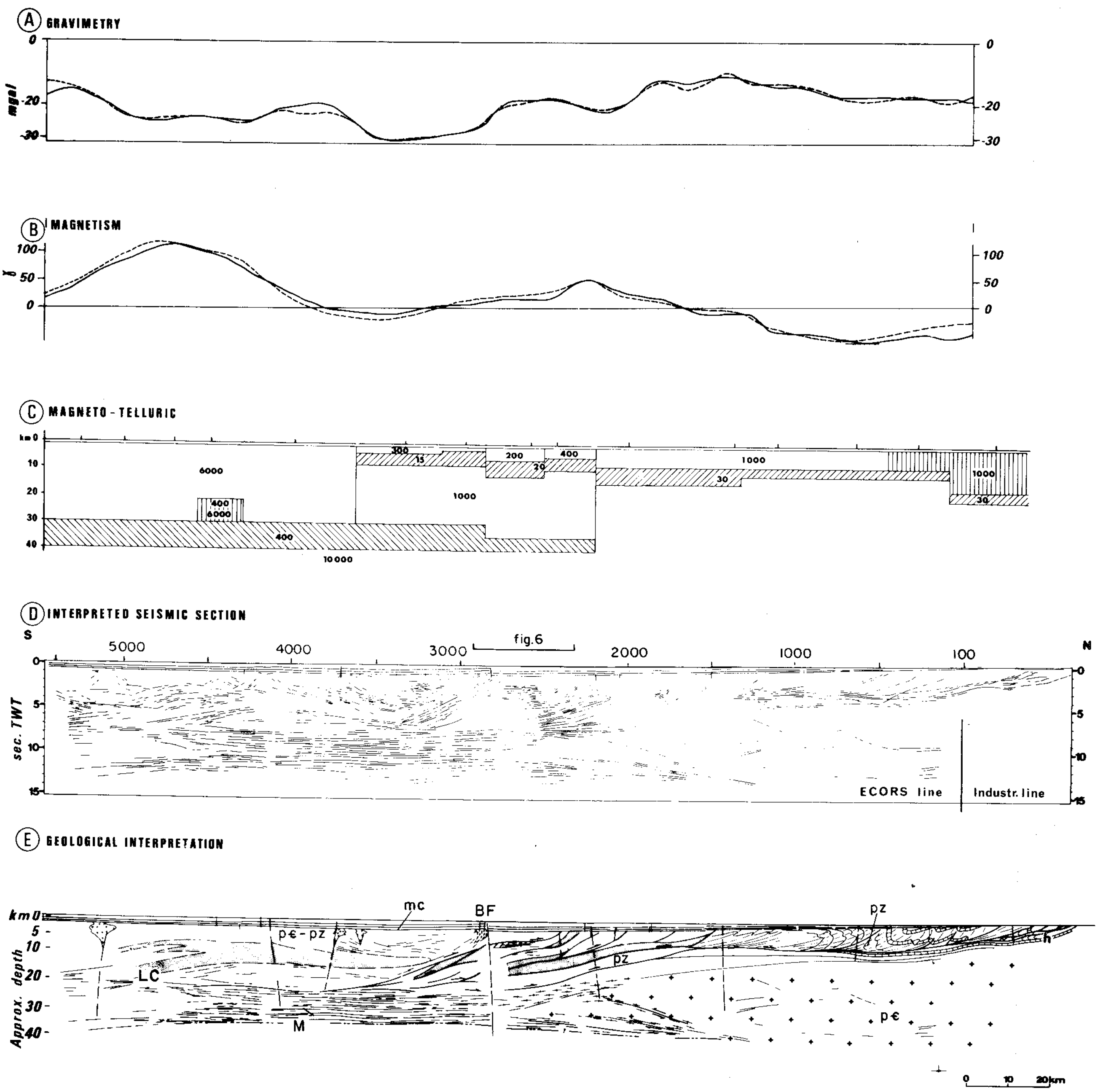


Figure 5.- Geophysical results of the ECORS northern France profile and their geological interpretation (modified from Cazes *et al.*, 1986).

A: (1) vibroseismic line-drawing, (2) vibroseismic line-drawing after migration, (3) explosive seismic line-drawing, (4) geological interpretation. Abbreviations Mr, Ct, etc. indicate wells drilled down to the Paleozoic basement.

B: (1) gravity (plain line = data, dahed line = modeling, model of density in g/cm³ (2) magnetism (solid line = data, dotted lines = modeling, model of magnetism contrast in ampere/m), (3) aeromagnetism recorded in 1985, (4) magnetotelluric (model of resistivity in ohm-metre).

whole Paris basin. The origin of this anomaly is still debated (Gérard & Weber, 1971): basic intrusions related to major Precambrian or Variscan crustal faults or sedimentary magnetic bodies of Precambrian age. Gravity lows are interpreted as granite intrusions or Permo-Triassic basins. Gravity and magnetic highs, generally of smaller size, are regarded as basic intrusions.

The Variscan fold belt resulted from a continental collision following the closure of one or several Paleozoic oceanic zones. One of them is assumed to have existed in the profile area until the Carboniferous (Matte & Burg, 1981). Paleontological and petrographic evidence upholds this view. Ophiolitic bodies, such as those found to the west in southern Cornwall (Lizard complex, Fig. 1) and to the east in the Münchberg area, might well mark this suture and could explain the small

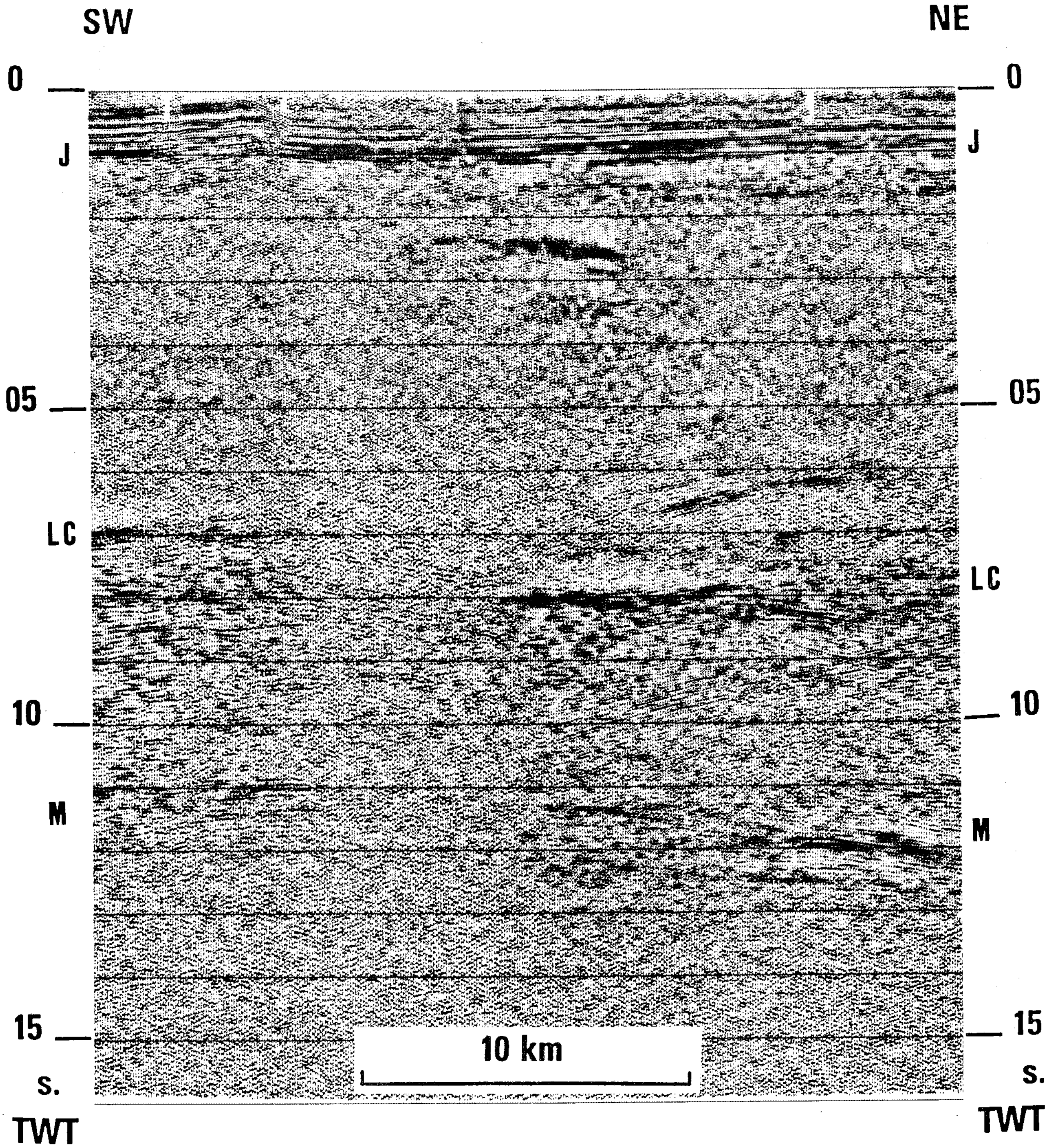


Figure 6.- Portion of the ECORS northern France profile illustrating the Bray fault (from Bois *et al.*, 1986). Note the layering of the lower crust between 8 and 10 s TWT. See location in Fig. 5. : J = bottom Jurassic, LC = top lower crust, M = Moho.

magnetic anomalies north of the Bray fault.

There are some ten wells on the profile or very near to it, which bottom out in Paleozoic formations. The recent Epinoy well (Epy in Fig. 5) in the north of the profile encountered the Midi fault overthrust at a depth of 2102 m and then cut across 2000 m of late Devonian and Carboniferous overturned series. A 30 km oil company line was used to connect the deep seismic profile to the Epinoy well and the outcrop of the Midi fault.

On the line-drawing of the profile (Fig. 5), three shallow horizons within 1 s TWT make up the sedimentary cover of the Paris basin. According to wells and previous seismic profiles, they are the top Kimmeridgian, the top Dogger and the bottom Jurassic.

Below this sedimentary cover, the northern segment of the section (Points 100-1500), is cha-

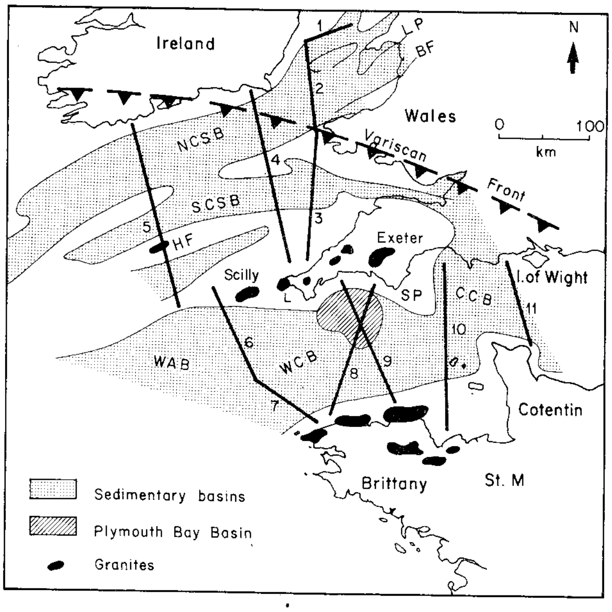


Figure 7.- Main structural features between England, France and Ireland and location of the SWAT profiles (solid lines) (modified from BIRPS and ECORS, 1986). Cornubian (SW England) and Brittany granites are shown in solid black. CCB = Central Channel basin, NCSB = North Celtic Sea basin, SCSB = South Celtic Sea basin, WAB = Western Approaches basin, WCB = Western Channel basin. Diagonal hachures mark the Plymouth Bay basin which underlies the Western Channel basin. HF = Haig Fras, L = Lizard, LP = Lleyn peninsula, SP = Start Point, ST M = Saint Malo.

racterized by a few south-dipping reflections merging into a band of low-angle to flat reflectors occurring between 3 and 5 s TWT. The top of this band can be identified as the Midi fault in the Epinoy well. Above it, the Dinant nappe has not been resolved by this type of seismic due to close folding and schistosity. Only a few subsidiary faults can be observed. Below the nappe, the reflections are interpreted as the autochthonous sedimentary cover of the Brabant foreland cut by the Jeumont well, only a few tens of kilometers east of the profile (Cazes *et al.*, 1987). This interpretation is also supported by the magnetotelluric results. Below the low-resistivity sedimentary cover, this method shows another low-resistivity layer (40-60 ohm.m) between two high-resistivity zones. This set of data strongly suggests that a Paleozoic sedimentary wedge extends southwards over more than 100 km below the Variscan frontal nappes. The transparent zone below 5 s TWT corresponds to the Brabant basement characterized by pervasive Caledonian folding, faulting and schistosity.

The central segment of the section (Points 1500-3000) shows many south-dipping reflections between 3 and 8 s TWT. They are interpreted as imbricated thrusts involving early Paleozoic and Precambrian rocks in which the decollement-shearing zone at the bottom of the Dinant nappe is rooted just on top of the lower crust around 8 s TWT. These thrusts, which occur in an area of gravity highs and magnetic anomalies, might also involve magnetic material such as basic and ultrabasic rocks and correspond to a suture in the upper crust. Magnetotelluric profiling found low resistivity here and a definite anisotropy related to the strong tectonic orientation.

In the southern segment (Points 3000-5400) the upper crust shows north and south-dipping events which should correspond to complex tectonic features in the inner part of the range as indicated by bottom samples from drill holes. The large magnetic anomaly might correspond to a comparatively transparent zone between 2.5 and 5 s TWT. It is not related to any obvious major crustal faulting.

The lower crust displays prominent layering below 8 s TWT in the two southern segments of the section (Figs 5 and 6). The lowermost trend of the reflections shows fair continuity and corresponds to the Moho, as confirmed by the wide-angle reflection experiments. This discontinuity is situated at a depth of between 36 and 40 km and shows an apparent dip to the north. The crustal layering and the Moho fade northwards in the area where the Brabant foreland underlies the Dinant nappe. However, a wide-angle experiment found the Moho reflection to be deeper there (Hirn *et al.*, 1987). The magneto-telluric results show a low-resistivity zone (400-600 ohm.m) with respect to the overlying and underlying media. This zone is situated at the same approximate depth as the layered lower crust, and it disappears to the north at the same place.

The origin of the lower crust's layering is still subject to debate. Whereas some have argued that it could be related to the Variscan orogeny, we now believe that it could be younger and result from an upward Moho readjustement following the crustal stacking and could be associated with lower crustal metamorphism and magmatism during the Permian and/or early Mesozoic times (Bois *et al.*, 1987, 1988).

The Bray fault was initially interpreted as a major fault cutting across the whole crust with a large vertical displacement. Re-processing and wide-angle data have later shown that the vertical displacement of the reflections was small, probably because the fault was mainly strike-slipping.

The overall picture of the northern France Variscan fold belt suggests the collision of the Brabant foreland against another block to the south. The suture between the two crustal blocks

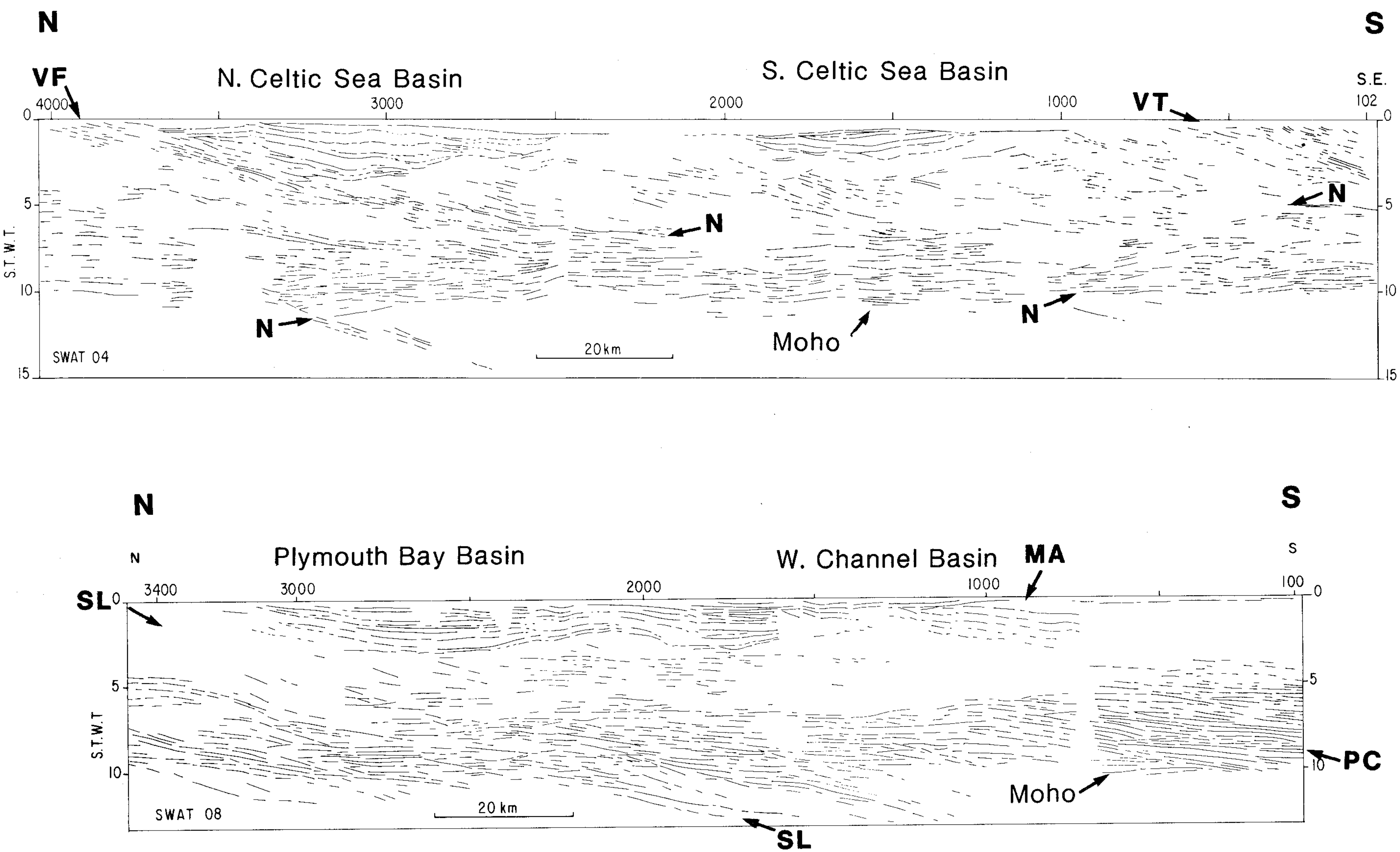


Figure 8.- Line-drawings of the SWAT 4 and SWAT 8 profiles. See location in Figs 1 and 7. MA = mid-Channel magnetic anomaly, N = north-dipping reflection, PC = mid-Channel Pre-Cambrian (?) feature, SL = Start-Lizard suture, VF = Variscan front, VT = Variscan thrust.

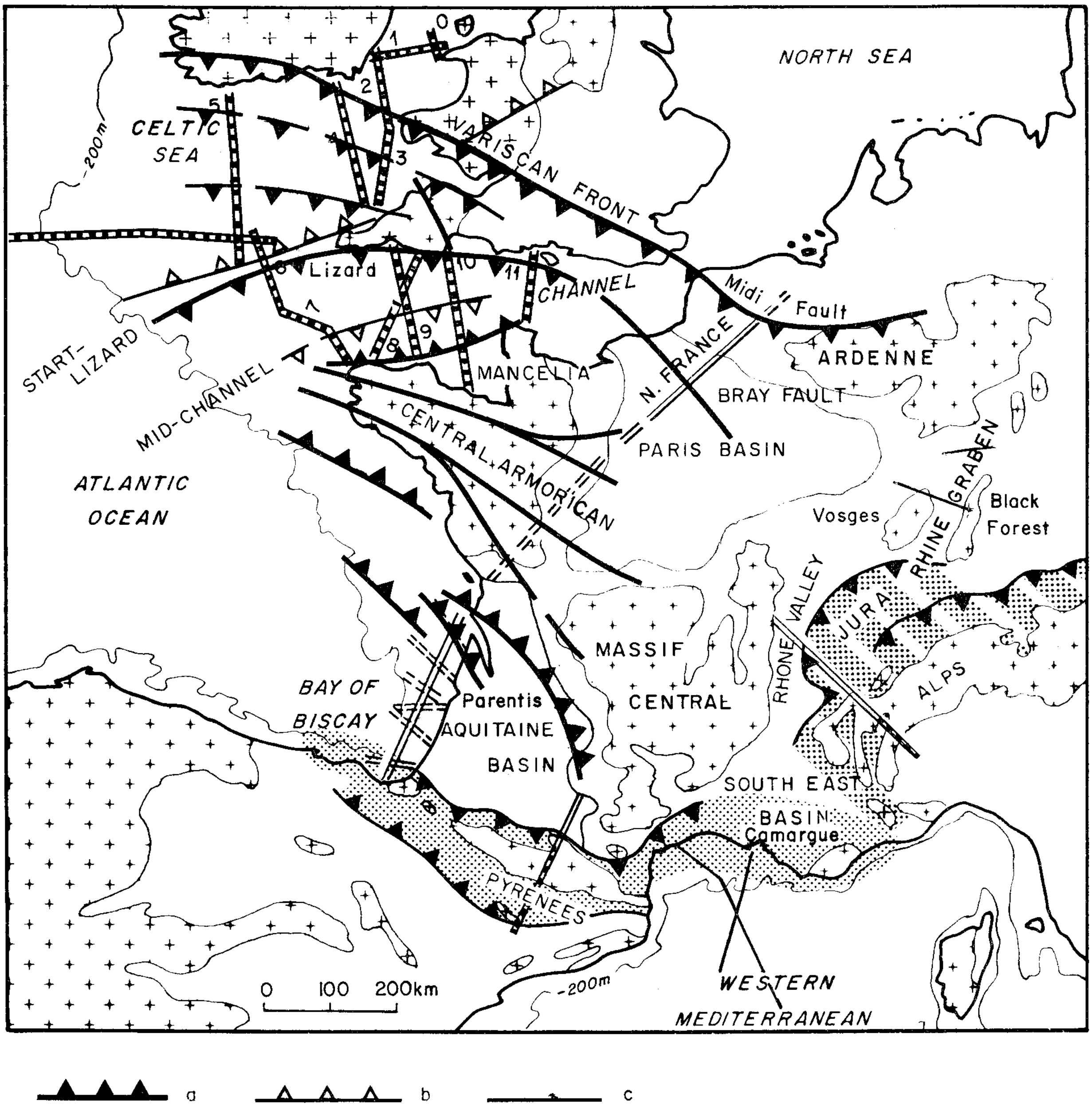


Figure 9.- Main features of the crustal structure in the Celtic Sea, the English Channel, southern England and western France from the deep seismic investigation. Same geological legend as Fig. 1.
a- Variscan thrust, b- pre-Variscan thrust, c- Variscan strike-slip fault.

may be marked in the upper crust by the magnetic material north of the Bray fault. There are, however, only faint indications of this suture within the lower crust. A few gently south-dipping seismic events cross the horizontal layering of the lower crust south of the Bray fault. they are more conspicuous in the southernmost portions of the section where they seem to extend into the upper mantle.

FURTHER INFORMATION ON THE VARISCAN FOLD BELT

The Variscan orogenic belt was also investigated by the SWAT project operated by the BIRPS group with the coopoeration of the ECORS project. On the north-south SWAT 4 profile (Figs 7 and 8), the frontal detachment was also found to extend over about 100 km from outcrop to root and to die out on top of the layered lower crust around 8 s TWT (BIRPS & ECORS, 1986). It shows however neither extensive flat nor imbricated thrusts such as in northern France. Likewise,

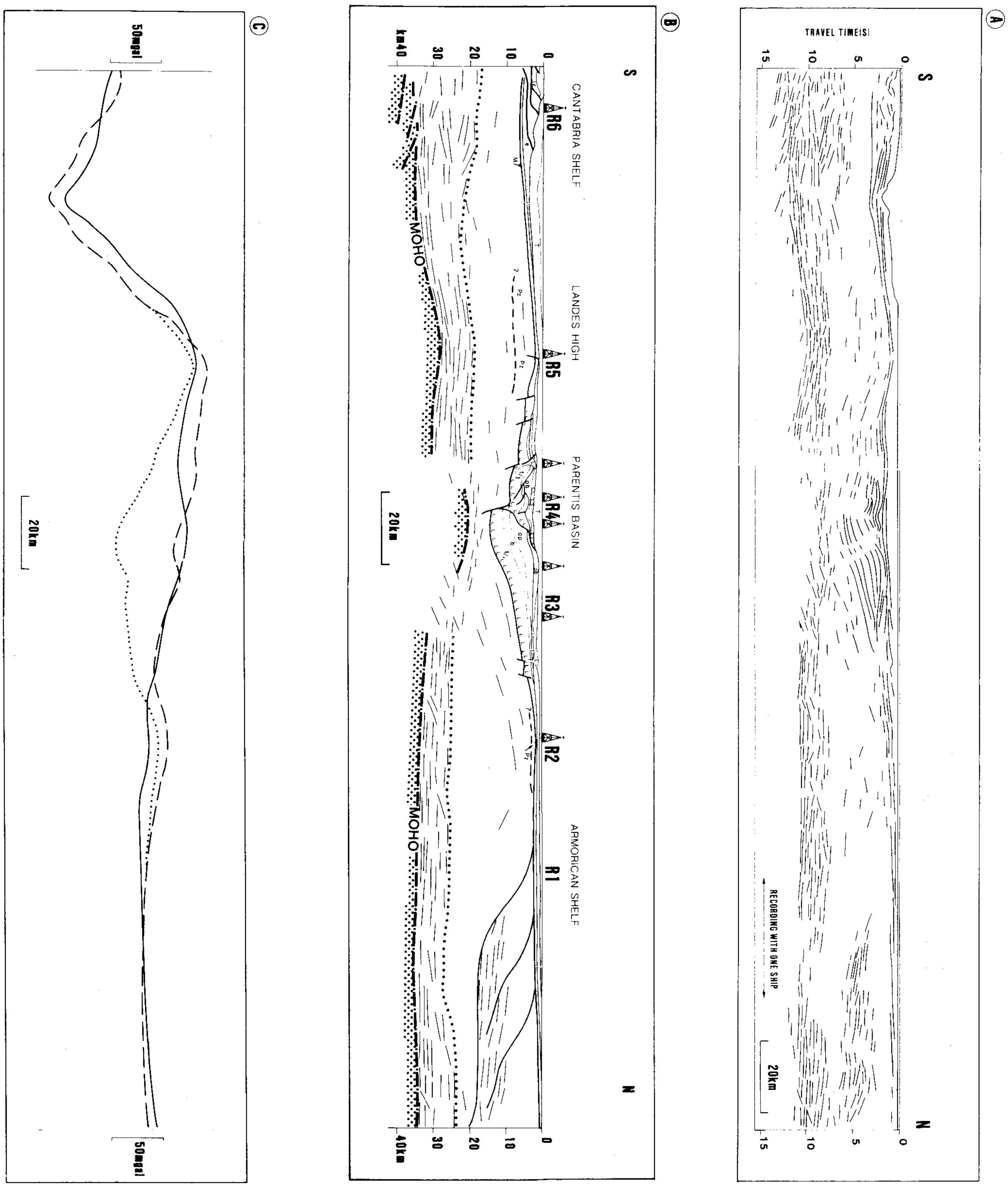
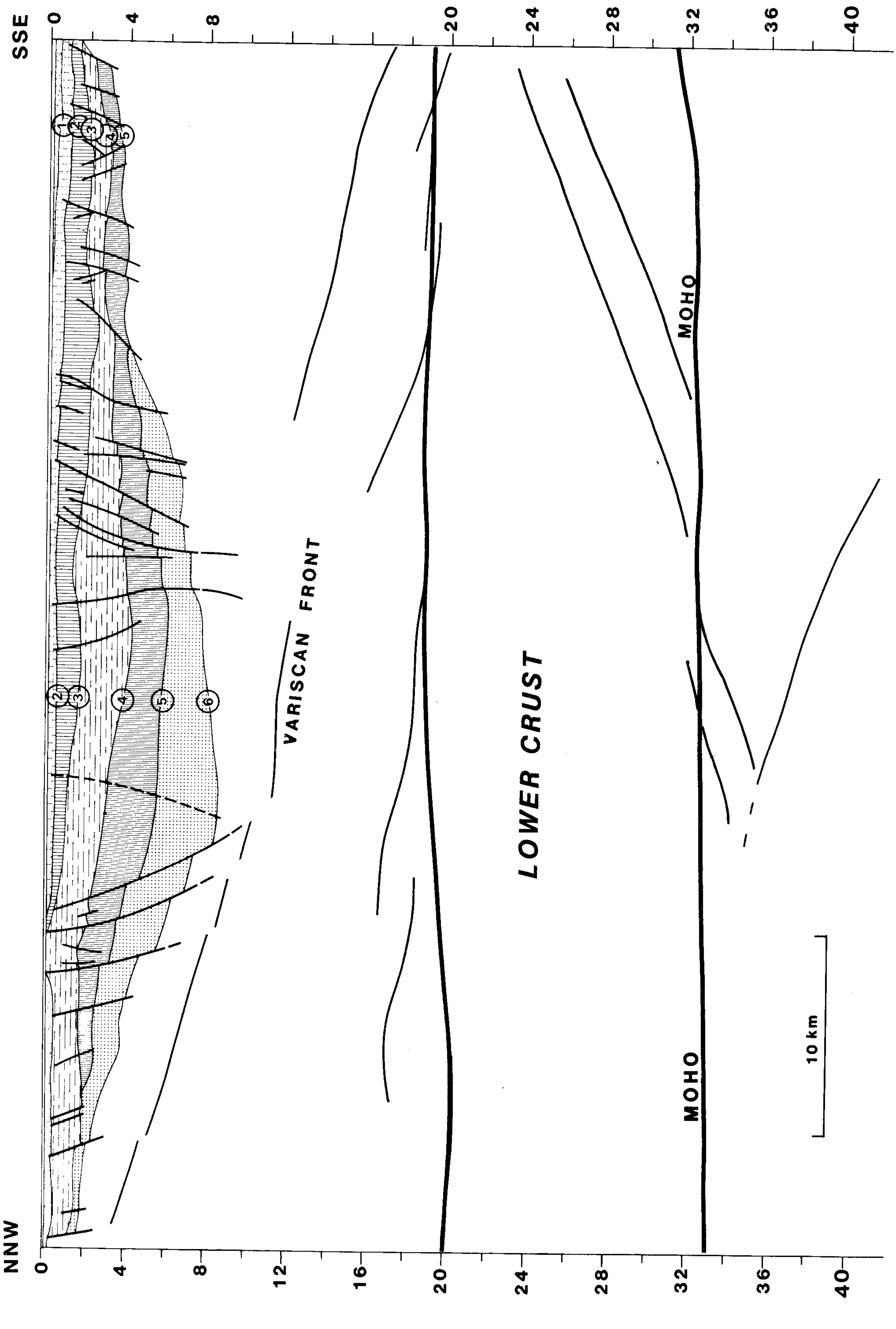


Figure 10.- Interpretation of the ECORS Bay of Biscay profile (from Pinet *et al.,* 1987).

a- TWT simplified line-drawing, b- geological interpretation (the section is in km and in true scale). The locations of six ESPs (R1 to R6) and petroleum boreholes are indicated at the top. T = Tertiary, M = Mesozoic, PZ = Paleozoic sediments, O = Oligocene, E = Eocene, LC = Cretaceous, ab = Albian, ap = Aptian, b = Barremian, t/j = undifferentiated Triassic and Jurassic, c = Gravity models drawn from Fig. 10 b = the dashed line assumes mantle updoming beneath the Parentis basin, the dotted line shows a flat Moho, and the solid line represents the data observed.

Figure 11.- Depth section of the North Celtic Sea basin along the SWAT 4 profile. Seismic waves velocities from the stack velocities.▼
1- top late Cretaceous, 2- top early Cretaceous, 3- top late Jurassic, 4- top middle Jurassic, 5- top Triassic, 6- top basement.



SSE
NNW
0
4
8
12
16
20
24
28
32
36
40
VARISCAN FRONT
LOWER CRUST
MOHO
MOHO
10 km

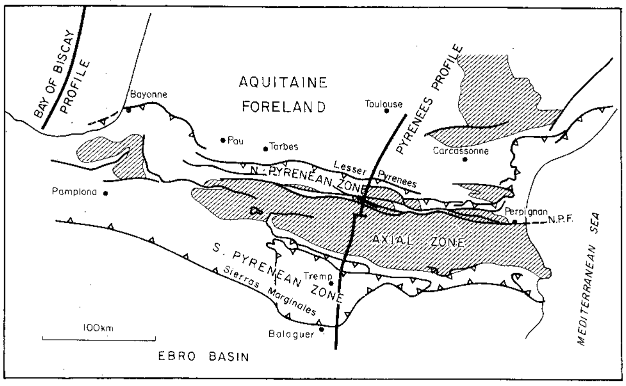


Figure 12.- Location map of the ECORS Pyrenees profile carried out by the French-Spanish association (after ECORS Pyrenees team, 1988). NPF = North Pyrenean fault. Diagonal hachures = Variscan basement.

there is no evidence of any sedimentary wedge beneath the detachment. These changes may be caused by the different orientations of the profiles with respect to the main direction of tectonic transport and/or actual changes in the front's geometry and shortening processes. Differences have been observed in the field between the set of thrusts associated with the Midi fault in northern France and the gradual decrease of the deformation in southern Ireland, leading some to question the concept of a Variscan front in the latter area (Matthews, 1984).

On both the SWAT and northern France profiles, the Moho remains comparatively flat below the layered lower crust as the result of the complete disappearance of the Variscan mountain roots. The traces of a number of Variscan thrusts can however be observed across the lower crust (e.g. the Lizard thrust, Fig. 8) and sometimes down into the mantle.

The SWAT and northern France profiles also provide a new insight into the areal framework of the crust within a large region in France and adjacent areas (Fig. 9). South of and beneath the Variscan front in the Celtic Sea, the crust is cut by major north-dipping features which seem to be older than the Variscan thrusts. They may be related to the Caledonian folds, faults and lineations which outcrop in Wales and southern Ireland. These features probably controlled most subsequent deformation in this area.

The Variscan Start-Lizard suture, lined by ophiolite sheets, forms the boundary between the Celtic foreland and the rigid Channel-Mancellia block. Within this block, the large mid-Channel magnetic anomaly may correspond to a late Pre-Cambrian south-dipping suture (Lefort, 1975). The Start-Lizard thrust seems to extend to the east and SE up to the area of the Bray fault where it may have been offset by this latter.

Several alignments of late Caroniferous granite batholiths indicate crustal thickening in the whole area. They suggest that the Variscan front and other thrusts in the Celtic Sea might go much deeper than the top lower crust and have involved the whole crust.

South of the Channel-Mancellia block, the Central Armorican block is another terrane where major strike-slip faulting, late Variscan in age, has considerably obscured the structure of the bottom of the crust (Matte & Hirn, 1988). Along this zone a northern area where Variscan structures are predominantly north-verging and a southern one where they are south-verging were welded together.

The southern boundary of the south-verging area can be observed in the northernmost part of the Bay of Biscay profile (Fig. 10). The upper crust, which is generally transparent, shows energetic laminations there, however less continuous and straight than the lower crust's ones. They are regarded as thrust sheets of a former lower crust related to a major Devonian event observed in the field on the southern edge of the central Armorican block (Pinet *et al.,* 1987).

THE BAY OF BISCAY PROFILE

The Bay of Biscay profile, 295 km long, was shot on the continental shelf of the bay (Fig. 1). It crossed the Triassic-Jurassic Aquitaine basin from the southern Armorican shear zone down to the Pyrenees front. In its central part, the profile cut across the Parentis basin, a narrow trough superimposed on the Aquitaine basin during the onset of the Bay of Biscay's opening in the early Cretaceous. The main objective of the profile was to elucidate the structure of the crust beneath this basin.

On the line-drawing and its geological interpretation (Fig. 10), the Parentis basin, more than 10 km deep, displays a half-graben shape (Pinet *et al.,* 1987). It was mainly infilled by thick clastic sediments during the early Cretaceous. The continental break-up and the formation of an oceanic crust in the Bay of Biscay were completed in the late Aptian to early Albian. Almost immediately after, a compressional event inverted existing normal faults. Then subsidence resumed, and a second inversion and a gentle warping of the whole Parentis area resulted from the main regional compression which formed the Pyrenees in the Eocene. The thick Triassic evaporites contributed to the deformation during both the rifting and inversion phases.

The most spectacular feature on the profile is the very great crustal thinning which affects both

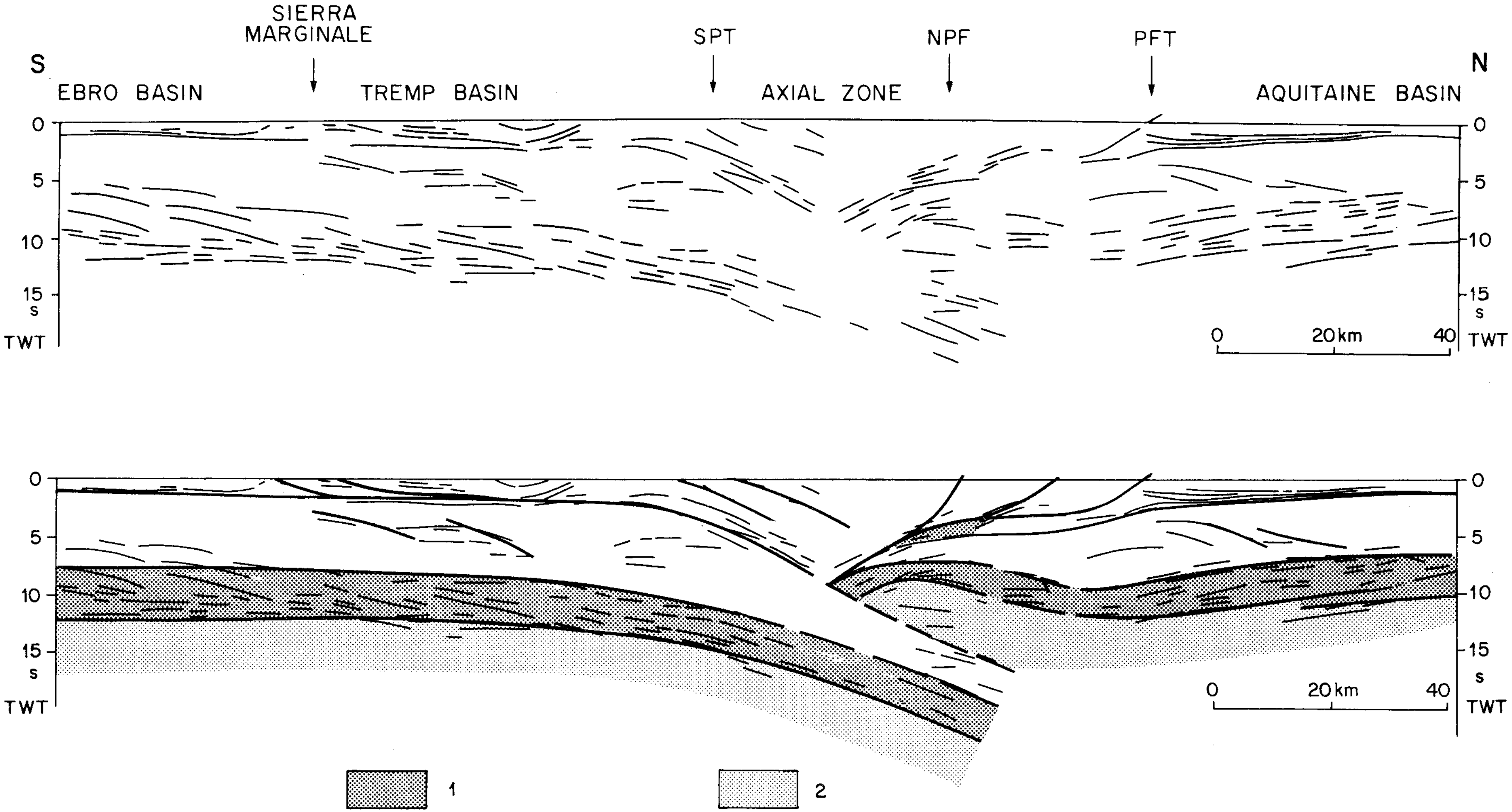


Figure 13.- Preliminary line-drawing of the ECORS Pyrenees profile (a) and a tentative interpretation among others (b) (from ECORS Pyrenees team, 1988).
NPF = North Pyrenean fault, PFT = Pyrenean front thrust, SPT = South Pyrenean thrusts and nappes, 1 - lower crust, 2 - upper mantle.

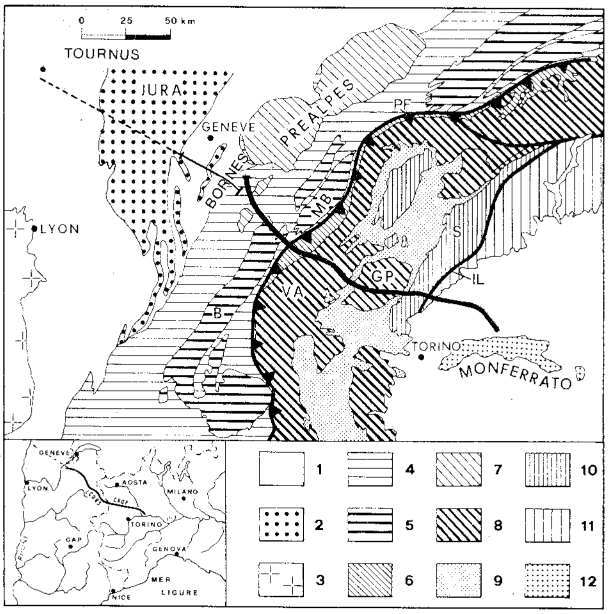


Figure 14.- Location map of the Alps ECORS-CROP profile carried out by the French-Italian association (after Bayer *et al.,* 1987).
Heavy line = segment of the seismic profile presented in this paper. 1- late and post-opogenic cover, 2- Jura-Mesozoic cover, 3- Massif Central basement. External zones: 4- outer sedimentary thrust sheets and nappes, 5- External Crystalline Massif. Internal zones: 6- Valaisan zone, 7- Pre-Alpine klippe, 8- Briançonnais zone and Internal Crystalline Massif, 9- Schistes lustrés and ophiolites, 10- Sesia-Dent Blanche unit, South Alpine domain : 11- Ivrea zone and undifferentiated South Alpine units, 12- Torino and Montferrato hills. PF = Penninic front, IL = Insubrian line, GP = Gran Paradiso, B = Belledone, MB = Mont Blanc, SL = Sesia-Lanzo, VA = Vanoise.

upper and lower crusts over a 60 km width beneath the rifted Parentis basin (Marillier *et al.,* 1987). This thinning and the corresponding Moho uplift are inferred from the seismic reflection, ESP interpretation and two-dimensional gravity modeling. The presence of this thin crust and the corresponding Moho uplift are obviously related to the proximity of an oceanic domain, with the Parentis basin being considered as a failed arm of the oceanic Bay of Biscay. The high velocity (6.7 km s^{-1}) found beneath the Parentis basin suggests pre-oceanization of the attenuated crust by mantle intrusions.

Later crustal shortening resulting in inversion and strike-slipping of the faults has contributed to giving the basin its present shape and make any accurate reconstruction of the subsidence difficult. However, it is clear that there is a major discrepancy between the small amount of horizontal extension by faulting and the great crustal thinning observed on the sections.

THE NORTH CELTIC SEA BASIN

A very similar conclusion may be drawn from the study of the North Celtic Sea basin which underwent a geological history in many respects similar to the Parentis one, but only suffered gentle inversions. This basin is 450 km long and only 60 km wide (Fig. 7). Some have claimed it to show a good example for the simple shear model in great vogue at present (BIRPS & ECORS, 1986; Cheadle *et al.,* 1987; Gibbs, 1987; Beach, 1987). The oblique detachment responsible for the basin's formation would be the Variscan frontal ramp which outcrops farther to the north and would have been reactivated as a normal fault since the Permo(?)-Triassic.

According to this hypothesis :

(1) The basin should be parallel to the Variscan front. The map shows the opposite situation and the basin even extends beyond this front in the Saint George Channel.

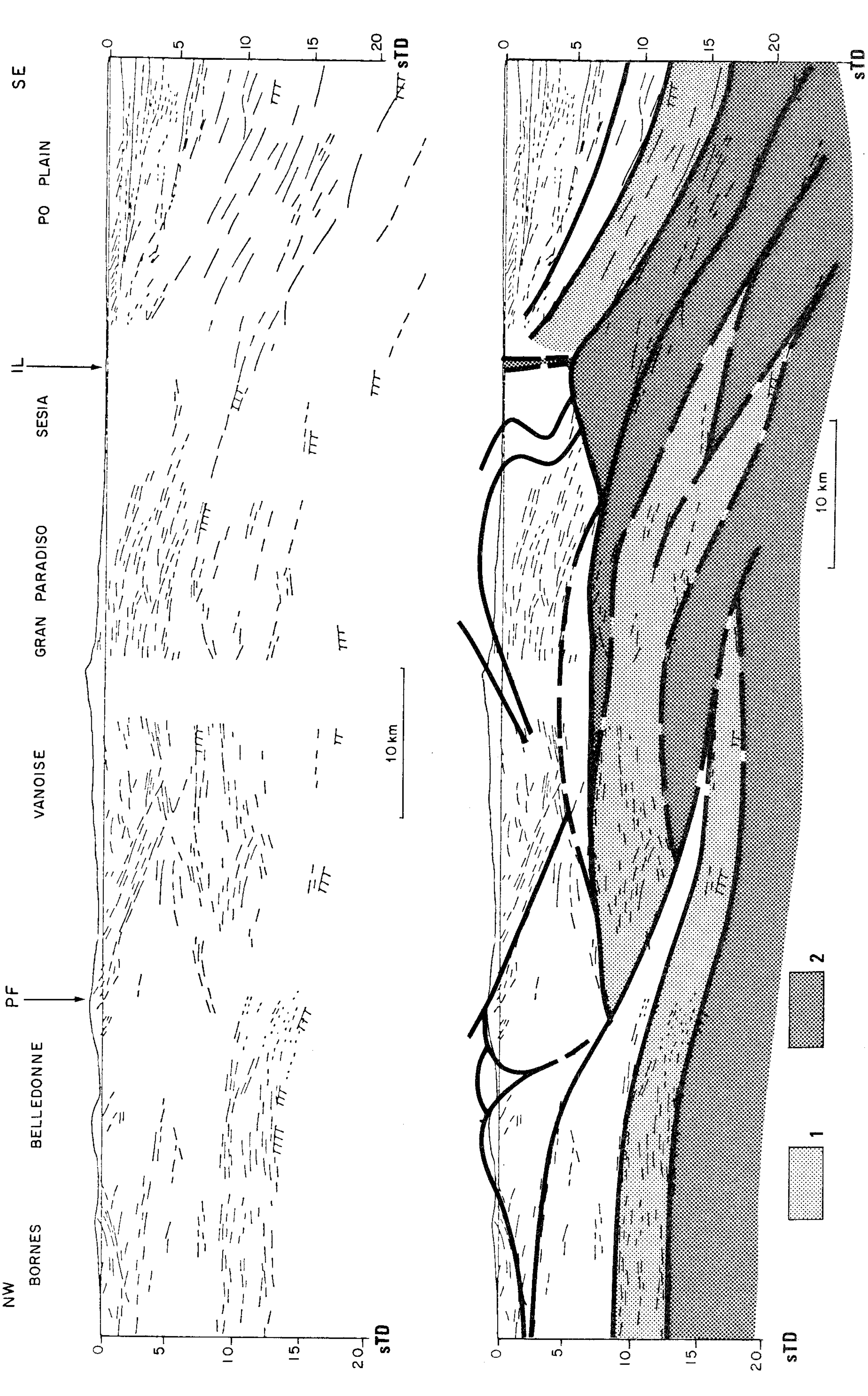
(2) The detachment controlling the subsidence should correspond to the top of the basement in the northern limb of the basin; we observe this detachment deeper than the basement. Moreover, this later should not have been cut by a number of faults active since the beginning of the subsidence (Fig. 11).

(3) The model predicts that the depocenters should have been gradually shifted northward along the detachment. We observe the opposite situation.

The pure shear model would better account for the comparatively symmetrical shape of the basin. However, the rift and post-rift stages of this model cannot be easily identified. At least two rift phases were superimposed as in Parentis, and the faults were active in one place or another from the Permo(?)-Triassic to the late Cretaceous. These faults generally show moderate throws and no real tilting of the layers. The lower crust does not show any attenuation beneath the basin. Moreover, the preservation of Paleozoic dipping features in the crust precludes any major lateral transfer of crustal material. The whole picture does not fit in with major crustal extension and is more suggestive of a gentle thermal subsidence.

Both the North Celtic and Parentis basins show a striking discrepancy between the small horizontal extension accomodated by the faulting

Figure 15.- Preliminary line-drawing of the Alps ECORS-CROP profile (a) and a tentative interpretation (b) (modified from Bayer *et al.,* 1987).
The short markers underlined by diagonal ruling correspond to the Moho or a dense body from a wide-angle preliminary experiment. IL = Insubrian line, PF = Penninc front.



NW
SE
BORNES
BELLEDONNE
PF
VANOISE
GRAN PARADISO
SESIA
IL
PO PLAIN
0
5
10
15
20
sTD
10 km
1
2

and the much larger thinning of the crust (Pinet *et al.*, 1987). Beneath the Parentis basin, both the upper and lower crusts were thinned, while only the upper crust was attenuated beneath the North Celtic basin. These observations suggest that crustal thinning was mainly achieved by crustal sagging followed by metamorphism and magmatism in the deep crust and uplift of both the mid-crust and Moho discontinuities. These processes would have reached a more advanced stage beneath the Parentis basin which is nearer to the ocean.

THE PYRENEES PROFILE

The Bay of Biscay profile also shows the north-vergent thin-skinned tectonics corresponding to the northernmost features of the Pyrenees frontal deformation (Figs 10 and 12). In this southern end of the profile, the Moho deepens rapidly, showing a southward flexure of the crust which seems associated with an overall thickening of the lower crust.

The Pyrenees profile, carried out 300 km farther east, crossed the whole fold belt (Figs 1 and 12). This profile, 255 km long, went through

(1) the Aquitaine foreland overlain by a molassic basin,

(2) the northern Pyrenean zone characterized by Variscan basement cores and late Cretaceous flysch,

(3) the axial zone made of Variscan material reworked by south-verging Pyrenean thrusts, and

(4) the southern Pyrenean zone where a wide Meso-Cenozoic basin (Tremp basin) was largely detached and thrust over the Ebro molassic basin along the Sierras Marginales.

The lesser-Pyrenees and Pyrenees front thrusts are located to the north of the North-Pyrenean zone. The boundary between this zone and the axial zone is marked by the North-Pyrenean fault, a major vertical feature which played a prominent part during the pre-orogenic history as the southern limit of the European plate attenuated and overlain by a thick Cretaceous basin. Along this fault, strong deformation and metamorphism occur within a narrow band where bodies of mantle material outcrop.

The preliminary line-drawing in Figure 13 shows quite good reflections in the whole crust displaying an overall fan shape (ECORS Pyrenees team, 1988). The laminated lower crust and the Moho are fairly clear on both sides of the profile. They outline a major north-dipping flexure of the southern Iberian plate while the northern European one shows gentler southern dips. In between, the triangular shape of the axial zone results from interference between the diverging structures of the two limbs of the fold belt. It is difficult to trace the boundary between the Iberian and European plates down to the mantle and to assess the role of the North-Pyrenean fault during the compression at this stage of the interpretation. The tentative model in Figure 13, among others, implies that the Iberian plate bounded by the North-Pyrenean fault was punched by the European plate during the compression. The upper crust and its sedimentary cover were popped up and thrust on both sides of the contact, while the middle and lower parts of the Iberian crust were underthrust beneath the edge of the European plate.

THE ALPS PROFILE

The Alps profile was planned to cross the whole deformed belt from the Monferrato hills near Torino to the basement outcrop on the edge of the French Massif Central (Figs 1 and 14). The first segment of this profile, 240 km long, was completed in 1986. We shall present preliminary results of this survey which crossed

(1) the Po plain,

(2) the suture zone including the Insubrian and Viu-Locana lines bounding the Sesia Massif,

(3) the Internal Zones including ophiolite, schistes lustrés, Internal Crystalline Massif (Gran Paradiso), the Briançonnais (Vanoise) zone and the narrow Valaisan zone,

(4) the External Crystalline Massif (Belledone) and

(5) the outer sedimentary thrust sheets and nappes (Bornes).

The boundary between the Internal (2 and 3) and External (4 and 5) Zones is marked by the Pennic front, a major thrust system which has been active since the beginning of the Alpine collision.

On its NW end, the preliminary line-drawing in Figure 15 shows the European deep crust characterized by the usual layered zone overlying the Moho located around 12 s TWT (Bayer *et al.*, 1987). This lower crust displays a gentle northward flexure beneath the Externides nappes (Bornes, Belledone). A trend of SE-dipping reflections marks the basal detachment of the External Crystalline Massif which emerges beneath the Bornes nappe. The Gran Paradiso domal shape is clearly imaged on the section although the west-dipping markers on its westrn edge might also indicate late Alpine back-thrusting. The steep structures which characterize the suture zone give a blank down to 5 s TWT. The Po plain displays a thick sedimentary wedge down to 6-7 s TWT on the eastern end of the profile.

The structure of the deeper part of the range is more difficult to interpret because the layering of the lower crust and the Moho fade out southeastwards below 13-14 s TWT. A preliminary wide-angle experiment carried out in 1985 provides some indications on the Moho depth unfortunately in areas somehow offset with respect to the profile. This experiment also shows the presence of a dense body at 6 s TWT beneath the Vanoise, possibly a thin mantle thrust sheet overlying a piece of laminated lower crust down to 9 s TWT. The dipping reflections of the Penninic front are rooted on top of this thrust sheet. At this stage of the study, the deeper zones may be interpreted in different ways.

According to the schematic model in Fig. 15, several imbricated thrusts involve the European lower crust and mantle west of the lithospheric suture zone. Above 6 s TWT, the European upper crust was largely detached from these imbricated thrusts and followed its own shortening pattern in the Internal domain.

CONCLUSION : REMAINING QUESTIONS

The data we have briefly reviewed examplify a complete geologic cycle including

(1) the Variscan orogeny and the resulting crustal thickening,

(2) the stabilization of the crust and the mountain root disappearing,

(3) the crustal attenuation, rifting, subsidence, and ocean opening,

(4) the Alpine collision, orogeny and new crustal thickening.

Much has still to be done to draw all the details from these date, especially from the recent Pyrenees and Alps profiles. However, besides outlining the major structural features of the crust, the deep seismic profiles have also contributed to focus our attention on major geodynamic problems. While most Earth scientists agree on the fact that active margins and orogenies result from plate convergence, there is more controversy on the formation of passive margins. The processes which affected the deep crust and led to the mountain root disappearing, the lower crust's layering and the crust attenuation beneath sedimentary basins and continental margins remain to be elucidated. These questions can very well be studied in France and neighbouring areas and they require the deep seismic investigation to be carried on.

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Discussion of the paper presented by Mr. C. BOIS entitled : MAJOR CRUSTAL FEATURES DISCLOSED BY THE ECORS DEEP SEISMIC PROFILES

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The ECORS northern France, geotraverse ably interpreted by a group of scientists under the inspiring leadership of Mr. C. Bois of the Institut Français du Pétrole (I.F.P.), certainly represents a most interesting contribution to a better understanding of the Hercynian substratum in the region. Having read publications on this ECORS subject and heard other oral exposé's, the writer cannot escape the feeling, however, that they invariably deal with only one interpretation of the seismic data at hand, not mentioning, nor commmenting upon other hypotheses expressed on the subject in general.

The writer has been involved in advancing such an hypothesis, the subject of a «Compte Rendu à l'Académie des Sciences de Paris» in 1985. This hypothesis deals with an initial graben of Upper Paleozoic age, crossing the substratum of the Paris basin from east to west, offset by late Hercynian wrench faults. When extension and graben formation ceased, the crust reacted through visco-elastic relaxation and a tectonic depression formed on top of the graben. This depression became then filled with sediments which, in turn, provoked further subsidence. These phenomena lasted the whole of the Mesozoic during which the Paris basin developed. A great similarity thus exists between Paris and North Sea basins : both came into being because of the presence of initial grabens at depth, the Paris basin slightly earlier than the North Sea basin.

ECORS and other geophysical data in northern France do not seem to contradict the possible presence of a graben, below and south of the Bray anticline, as witnessed there by :

- the high conductivities, deduced from the magneto-telluric measurements along the geotraverse,
- the strong, negative Bouguer gravity anomalies, the so-called «fossé gravimétrique», already interpreted years ago as representing a graben at depth,
- the published ECORS seismic data which strongly suggest the presence of a deep tectonic trough.

Below the Mesozoic, ECORS interpreters arrive at the most at a 600-metre deep «Permo-Triassic(?)» depression, while the graben, if present, would be thousands of metres deep, filled with Upper Carboniferous and Permian strata, the latter constituting a major challenge to find out whether they contain hycrocarbons or not.

Discussion on the paper

MAJOR CRUSTAL FEATURES DISCLOSED BY THE ECORS DEEP SEISMIC PROFILES - A reply

C. BOIS

The idea of a Paleozoic graben beneath the Mesozoic cover of the Paris basin has been proposed by several authors (Durandau & Koning, 1985). It is in line with subsidence model proposed by McKenzie (1978) and the discovery of the North Sea and Western Siberia graben systems beneath Mesozoic and Tertiary cratonic basins which are similar in shape to the Paris basin (Ziegler, 1982; Kontorovich *et al.,* 1975). Unfortunately, the ECORS northern France profile was not properly located to provide a definite conclusion to this puzzling question. This profile is located on the northwestern edge of the basin, almost 100 km from its deepest part where the greatest rifting should occur. However, on the basis of the seismic, gravity and magneto-telluric data collected along this profile, Dr Koning suggests the presence of a thick Paleozoic graben beneath and south of the Bray anticline. We shall review the data at hand.

1. On the seismic section, the early Jurassic reflector generally overlies a number of multiple reflections among which the basement cannot be easily picked. Therefore, a seismic refraction survey was carried out along the profile using the same recording spread as the seismic reflection survey and dynamite blasts were shot at offsets of 0, 15 and 30 km (Bois *et al.,* 1986). The seismic refraction shows a 6-km/s marker, identified as the Paleozoic basement in a few drill holes. The depth of this marker shows a definite discrepancy with respect to the depth of the bottom Jurassic south and north of the Bray fault (Mascle & Cazes, 1987). The maximum difference in depth between the two markers does not exceed 600 m. It is interpreted as evidence of sedimentary wedges having moderate thickness between the bottom Jurassic and the basement, the age of which may extend from the late Triassic to the late Carboniferous. The possibility of a large graben is thus rather remote. This should mean that the refraction marker was misinterpreted and was confused with a high-velocity layer overlying sediments, for instance a Permian lava flow. There is, however, only limited space to place any large graben between the wells which bottomed out in the Paleozoic basement on the profile or very near it. Moreover, the SWAT profiles shot in the nearby English Channel (BIRPS & ECORS, 1986) show that thick Permo-Triassic series are quite visible on the seismic sections in contrast to the hypothetical graben of the same age beneath the Paris basin.

2. The magneto-telluric data show a low-resistivity layer (15-20 ohm.m) on both sides of the Bray fault. This layer, 5 to 12 km deep is separated from the Mesozoic cover by a higher resistivity layer (100-400 ohm.m). This resistivity distribution was regarded by the ECORS scientific team as the expression of the imbricated thrusts in which the frontal Variscan nappe is rooted (Phan Van Ngoc, 1988). It may also be interpreted as a sedimentary wedge overlain by a high-resistivity layer (e.g. lava), but the wells have nowhere evidenced such a layer.

3. The gravity data were modelled using the structure drawn from the seismic profile (Galdeano & Guillon, 1988. After removing the influence of the Mesozoic sedimentary cover, the residual anomalies were only 10 milligal high and had a very short wavelength. The largest one, south of the Bray fault, could be explained by two extreme models : (1) a 1-km thick layer of Paleozoic sediments or (2) a 4 to 5-km thick granite body. The gravity data could not discriminate between these two solutions but they certainly disproved the existence of a thick sedimentary wedge beneath the Mesozoic cover.

The problem of Paleozoic grabens concealed beneath the Mesozoic cover of the Paris basin certainly deserves further attention. It first raises major geodynamic questions : should a rifting stage always be present before the gentle (thermal) subsidence of cratonic basins ? What might the age of such rifting be in the Paris basin case : Lias, Triassic or older ? Let us recall that the SWAT profiles did not find any obvious rifts beneath the Permo-Mesozoic basins in the English Channel and the Celtic Sea (BIRPS & ECORS, 1986). Anyway, the discovery of grabens filled by thousand of metres of Permo-Triassic sediments beneath the centre of the Paris basin should certainly also constitute a major challenge to hydrocarbon exploration. Such a possibility which should not be overlooked, requires the shooting of another deep seismic profile across the Paris basin, oriented approximately N-S and running in the Meaux-Coulommiers-Province area.

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