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A PROPOSAL FOR A COORDINATED PROGRAMME OF DEEP SEISMIC REFLECTION PROFILES ACROSS EUROPE

by

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(10 figures)

ABSTRACT.- Seismic reflection survey methods developed by industry for oil exploration now provide a means to image the crust and upper mantle with high resolution. Early work in the 1950's and 60's in West Germany was followed in USA with the Consortium for Continental Reflection Profiling (COCORP) set up in 1973 to explore the deep structure of North America. Groups established in European countries during the past six years have produced around 15000 km of deep reflection profiles, both onshore and offshore. They have discovered that major faults controlling sedimentary basins continue at low angle deep into the crust; that the lower crust is often, but not always, highly reflective and that the base of this reflective zone mostly coincides with the Moho. Major sutures between crustal provinces are marked by dipping features through the crust, interpreted as thrust faults possibly with duplex structures. A few reflections have been found in the upper mantle. These resemble reflections from faults in the upper crust. Interpretation of deep reflection profiles together with other geophysical and geological information is giving new impetus to understanding the rheological behaviour of the lithosphere when stressed, particularly in lateral tension and compression. This has particular significance for understanding basin development and architecture in various tectonic settings which can be expected to give practical help in oil exploration.

Although European groups have been collaborating closely in acquiring and interpreting deep reflection profiles, now is the time to consider a coordinated programme to create a network of deep seismic reflection profiles across Europe to link together the various findings on a continental scale. I have recently prepared proposals for the Commission of the European Communities with the following aims :

1) To provide a regional network of long profiles across the major structural elements of western Europe, in order to give a coherent and unified tectonic framework of the continent.

2) To provide detailed sections of the crust and upper mantle that comprise the lithosphere which in conjunction with other geological, geochemical and geophysical information will give a better understanding of the processes of continental crust formation and evolution.

3) To examine sedimentary basins in a variety of tectonic settings as a complement to oil industry data, in order to establish their structural and stratigraphical history, especially in their early stages when sedimentation and structural development are inter-related and acting at the same time.

The programme of profiles proposed, as shown in figure 1, thus sets out to address specific problems concerning the structure and evolutionary processes of the European continental crust as a whole, from the older, stable regions of the north to the younger, active regions of the Mediterranean, and the nature and evolution of sedimentary basins in a variety of tectonic situations. It is planned to do so with a network of long profiles that link together on a continental scale, together with shorter lines to investigate specific areas of critical interest. Advantage is taken of the cost effectiveness of lines at sea where possible, but balance this with lines on land according to the dictates of the geology.

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RESUME.- Les méthodes de séismique réflexion développées à l'occasion des prospections pétrolières permettent actuellement d'obtenir des images de la croûte terrestre et du manteau supérieur. Les premiers travaux réalisés au cours des décennies 50' et 60' en Allemagne Fédérale ont été suivis aux USA, dans le cadre des explorations commanditées par le «Consortium for Continental Reflection Profiling» (COCORP) pour l'étude des structures crustales profondes d'Amérique du Nord. Dans les six dernières années des groupes européens de recherche ont réalisé de leur côté quelque 15.000 km de profils séismiques profonds, tant sur terre que sur mer. Ils ont découvert que les failles principales qui limitent les bassins sédimentaires se prolongent sous de faibles inclinaisons dans les zones profondes de la croûte; que la croûte inférieure est souvent, mais pas toujours, caractérisée par de fortes réflexions et que la limite inférieure de cette zone à réflexion intense coïncide avec la discontinuité de Moho. Les principales provinces crustales sont séparées les unes des autres par des éléments structuraux qui pénètrent au travers de l'écorce, interprétés comme des failles de chevauchement. Quelques réflexions ont été mises en valeur dans le manteau supérieur. Elles présentent les caractéristiques des réflexions liées à des failles recoupant la croûte supérieure. L'interprétation des profils de séismiques réflexion profonde, associée à d'autres données de la géophysique et de la géologie, a relancé les recherches sur le comportement rhéologique de la lithosphère soumise aux tensions, particulièrement celles découlant de déplacements latéraux et de compression. Cette approche a permis d'améliorer nos connaissances sur le développement des bassins et sur l'aspect structural de diverses situations tectoniques, ce qui permettra d'aider pratiquement l'exploration pétrolière.

Bien que divers groupes de recherche européens aient travaillé en étroite collaboration, tant pour la mise en oeuvre que pour l'interprétation des profils séismiques, il est temps aujourd'hui d'élaborer un programme coordonné visant au développement d'un réseau de profils de séismique reflexion profonde au travers du continent européen. Dans cette perspective, j'ai préparé une série de propositions pour la Commission des Communautés Européennes, avec les objectifs suivants:

1) Constituer un canevas régional de profils de grande extension traversant les éléments structuraux principaux de l'Europe de l'Ouest, dans le but d'obtenir une image tectonique cohérente et unifiée du continent;

2) Présenter des sections de référence de la croûte et du manteau supérieur appartenant à la lithosphère qui, en relation avec les informations géologiques, géochimiques et géophysiques, apporteront de nouvelles données sur les processus de formation et d'évaluation de la croûte continentale;

3) Examinons les bassins sédimentaires dans divers contextes tectoniques en complément aux données recueillies par l'industrie pétrolière, dans le but de définir leur histoire structurale et stratigraphique, plus spécialement dans ses étapes initiales, au cours desquelles sédimentation et développement structural sont interconnectés;

Le programme des profils proposés, représentés à la figure 1, vise donc à rencontrer des problèmes spécifiques qui concernent la structure et l'évolution de l'ensemble de la croûte continentale européenne, depuis les régions anciennes, stables, du nord jusqu'aux régions plus jeunes, actives, de la zone méditerranéenne; en outre, il vise à mieux connaître la nature et l'évolution des bassins sédimentaires dans une série de situations tectoniques différentes. Cet objectif devrait être rencontré à l'intermédiaire d'un canevas de profils de grande extension connectés à l'échelle continentale, reliés à des profils plus courts couvrant des zones critiques spécifiques. L'ouvrage des faibles coûts de mise en oeuvre de la séismique en mer, là où la chose est possible, est balancé avec les opérations sur terre suivant les nécessités dictées par la géologie.

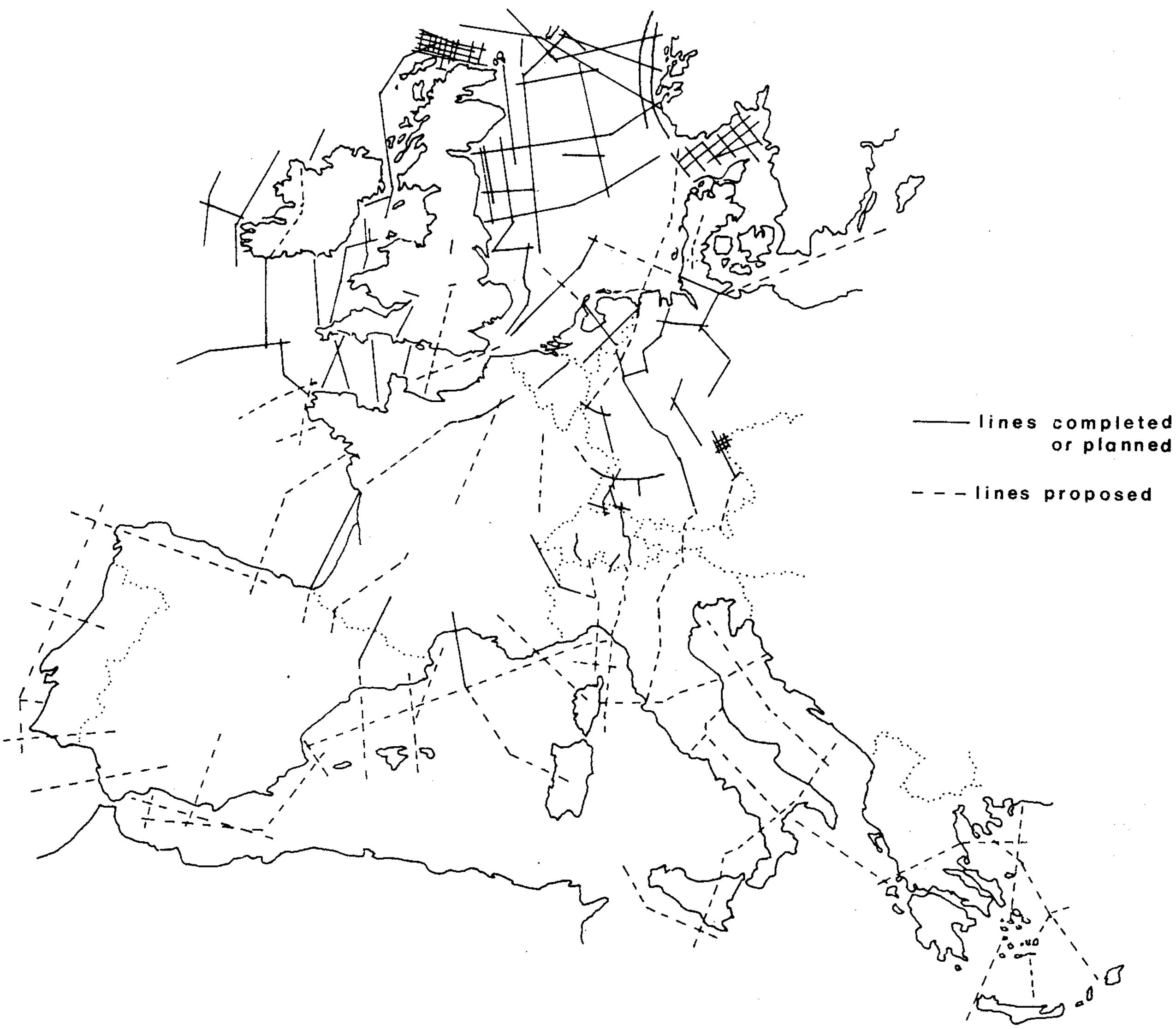

Figure 1.- Location map of existing, planned and proposed deep seismic reflection profiles across Europe.

1.- HISTORICAL DEVELOPMENT OF DEEP SEISMIC REFLECTION PROFILING

Since the advent of digital recording techniques in the 1960's and the subsequent huge increase in computing power the seismic reflection survey method has advanced, in the hands of the oil industry, to become an immensely powerful and highly sophisticated technique. Because of its success in hydrocarbon exploration field methods and procedures for data acquisition and data processing techniques have all been directed at elucidating the nature of sedimentary basins. The reflected seismic wavelets observed derive from the boundaries between sedimentary strata but usually result from constructive interfrence between individual reflections from a number of closely spaced interfaces a fraction of a wavelength apart. The oil industry is increasingly concerned with obtaining finer detail and, wanting higher resolution, consequently uses seismic sources generating shorter wavelength, higher frequency signals. But higher frequency waves are more rapidly attenuated with distance of travel, hence depth to reflector, than the lower frequencies so that compromises are made between resolution and signal strength for the deeper strata within a basin. It has been found that in general there is a considerable degree of lateral continuity in the character of individual reflectors along a profile, indicative of the lateral uniformity of the sediments. The compilation of traces through use of 'common mid-point (CMP) stacks' into composite 'zero-offset' traces and other processing techniques result in the enhancement of primary reflection signals. Continuity is normally

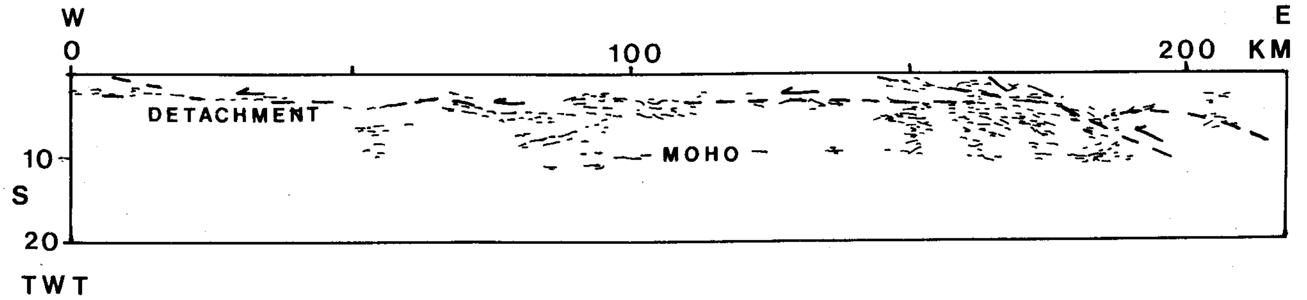

Figure 2.- Line drawing of COCORP Southern Appalachians Profile (from Brown *et al.*, 1986) showing the Appalachian Detachment.

established on stack sections by virtue of the phase coherence of the pulses rather than on their amplitudes, although preservation of relative amplitudes is quite often used in addition. The geometrical distortions of stack sections resulting from normal incidence reflections with non-vertical ray paths, etc. are reduced through 'migration' techniques which produce migrated record sections. The interpretation of seismic reflection surveys relies heavily on the ability to identify characteristic reflection signals that can be followed laterally across a network (usually a rectangular grid) of seismic profiles so that their three-dimensional geometry maps out the geological structure and their character and interaction with other reflectors helps determine the stratigraphy. Correlation with borehole logs of geological and geophysical parameters is an essential element of exploration.

Because the reflecting horizons of sedimentary strata are for the most part continuous and relatively flat lying it is these attributes that the seismic reflection method has been developed to enhance. Steeply dipping features, such as faults, are rarely seen directly as reflectors but are observed indirectly through the abrupt vertical displacement of sedimentary reflecting horizons and the generation of 'diffractions' at their terminations.

On most seismic record sections across sedimentary basins the continuity and clarity of individual reflectors decreases with increasing reflection time (TWT). This can be attributed to the increasing structural complexity of the older sediments in the basin, the reduction in the contrasts of acoustic properties between sedimentary strata at greater depth and the greater loss of seismic signal strength against 'noise' with increasing length of travel path. Quite often the loss of coherent reflections is fairly sharply defined and the zone below the lowest reflector on the record section is widely referred to as 'seismic basement' even though it may be known (through drilling) to be made up of sedimentary rocks.

The idea to use the seismic reflection method to explore deep into the crust was first tried out in West Germany during the 1950's by Dohr (1957) and later by Fuchs (1969) and Meissner (1967). They discovered that reflections could be obtained from deeper within the seismic basement and that the lower crust and the Moho (related to the crust-mantle boundary) are reflective. The techniques available to them at the time were such that signal to noise limitations prevented them from seeing specific features, but they were able, none the less to appreciate an apparent lack of lateral continuity of individual reflectors beyond about a kilometre. Their analysis of these early results has proved to be fundamental. Fuchs (1969), for example, showed that the reflections must derive, like those from sedimentary strata, from constructive interference between signals reflected off interfaces separating thin laminations with alternating higher and lower seismic propagation velocities.

With the development of the Vibroseis* source for land surveys during the early 1970's, in which a heavy vibrator truck generates a sweep of seismic oscillations, a greater signal strength could be built up by repeating the sweeps and stacking the successive recordings. This, and the advance in signal processing through CMP stacking led Oliver and Kaufman in 1973 to set up COCORP

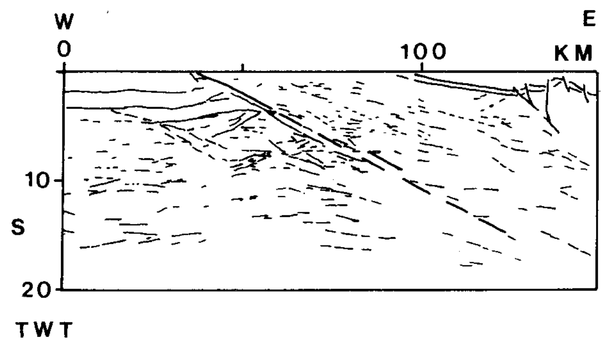

Figure 3
Line drawing of the COCORP Wind River Profile (after Brown *et al.*, 1986) illustrating the Wind River Thrust penetrating deep into the crust.

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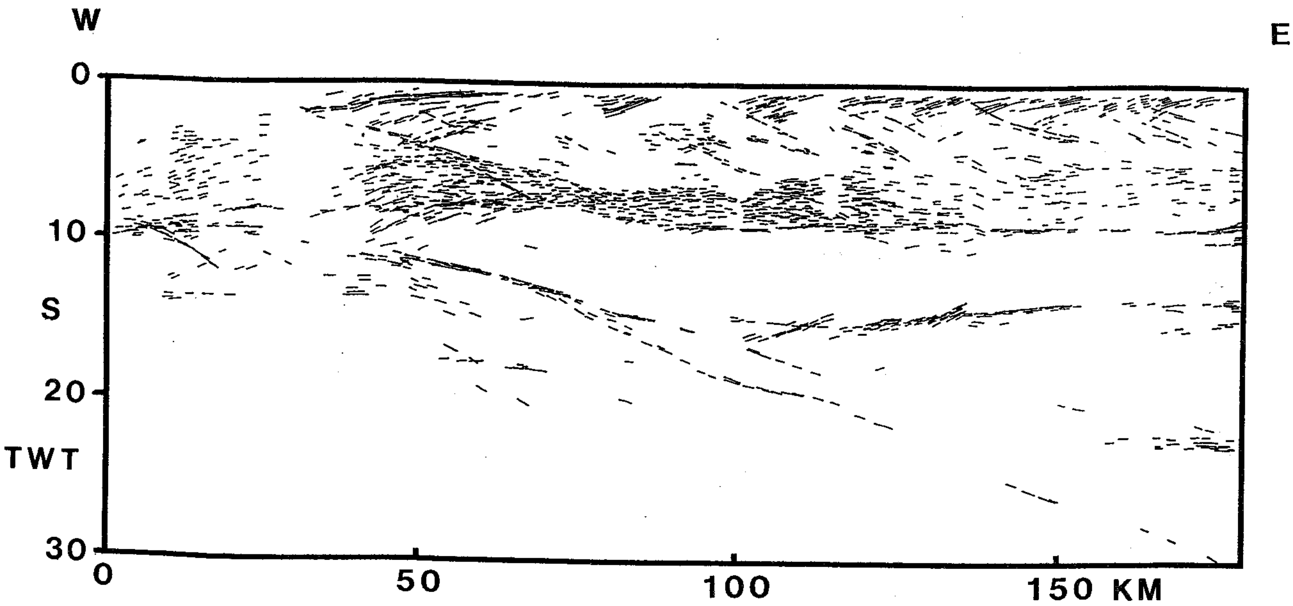

Figure 4.- Line drawing of the DRUM Profile north of Scotland (after McGeary & Warner, 1985) showing crust and mantle reflectors.

the Consortium for Continental Reflection Profiling, based at Cornell University, to utilise this improved technology to explore the deep crustal structure of USA. Apart from increasing the source energy and utilising the lower frequency range between 10 and 40 Hz (preferring to sacrifice some resolution for better signal to noise ratio at greater depths) they used standard oil industry exploration methods. However they recorded signals for 15 s TWT to look for reflections from as deep as 45 km. After an initial experiment across a sedimentary basin in Hardeman County, Texas (Oliver *et al.,* 1976) their efforts were mainly directed towards producing long (1000 km) profiles across major thrust belts, such as the Appalachians and the Wind River uplift. Subsequently they have profiled across the Basin and Range Province and the Michigan Basin and across tectonically active regions such as the Rio Grande Rift and Death Valley. Their first decade is reviewed by Brown *et al.* (1986). COCORP's formative contribution has been to demonstrate the effectiveness of the method, translated from oil industry use, in exploring deep into the Earth's interior with a resolution beyond all others. Their work led directly to the setting up of similar groups to use the same techniques elsewhere. In Europe this began with the establishment of BIRPS (British Institutions Reflection Profiling Syndicate) in 1981, closely folowed by ECORS in France and DEKORP in West Germany. Subsequently they have been joined by groups in Belgium, Italy, Netherlands, Norway, Spain, Sweden and Switzerland. Elsewhere, deep reflection profiling has been deployed for crustal exploration in Canada (Lithoprobe), Australia (ACORP) and by various groups in USA (USGS, CALCRUST and others).

The method is expensive and highly sophisticated and has in consequence been limited for purely scientific purposes to nationally formed groups in those countries that can afford it and have the technical expertise. The data acquisition and routine data processing have for the most part been undertaken by seismic contractors who normally work for the oil industry although this situation is now changing as universities and other institutions are gaining in resources and experience. Both COCORP and DEKORP now prefer to process the data themselves. The method is less expensive at sea, by a factor between 10 and 20, than on land. BIRPS has taken advantage of this to explore the continental shelf area around Britain rather than profile on land. At an average cost of about $ 300 per km for acquisition and processing using commercial contractors, BIRPS has obtained some 10 000 km of deep reflection profiles in six years. Overall in Europe about 15000 km of deep reflection profile has been acquired. As source, BIRPS use an airgun array, of which very powerfull versions have been developed by various contractors in recent years. Conventionally they have operated with a 3 km long hydrophone streamer producing 30 fold CMP stack sections recorded to 15 s TWT but in 1984 they recorded one line north of Scotland to 30 s TWT and discovered reflections in the upper mantle from depths in excess of 70 km. Working at sea has the advantage of a uniform upper layer, the sea, in which to work, so that reflection signal coherence is not degraded by heterogeneity in the uppermost 'weathered layer' which is difficult to combat on land through 'static' corrections. But it has the disadvantage of a relatively short maximum offset so that seismic velocity determinations for the crust below about 8 km are unreliable. This can be overcome by using a second ship towing a hydrophone streamer for expanding spread profiles (where both ships sail in opposite directions to maintain a common reflection point) or constant offset profiles in which one ship follows behind the other so they combine to simulate a wide array (of 9 km maximum offset). The cost per km is more than doubled in consequence. Alternatively, 'throwaway' sonobuoys can be used to record out to about 30 km offsets in a routine way.

Seismic acquisition on land is both more expensive and time consuming and technical problems from industrial noise, near-surface heterogeneity in the weathered layer, source coupling, loss of continuity through lack of access, etc. can hinder data quality. But, as both DEKORP and ECORS have demonstrated, opportunities to enhance the normal incidence data with observations of wider angle reflections using additional recording arrays offset both along profile and off-profile, for example in fans, are most effective on land. Although seismicity, heat flow, gravity and magnetic survey data can be interpreted in combination with the seismic data equally well on land or at sea, magneto-telluric measurements giving valuable information about electrical conductivity variations in the crust and upper mantle are effectively limited at present to the land areas. The surface geology of the offshore continental shelf is as well known as on land and borehole control is comparable. The major choice between working on land or at sea apart from cost has to be made in terms of the geological purpose of the work.

2.- THE ACHIEVEMENTS OF DEEP REFLECTION PROFILING

COCORP's attack on the thrust belts of USA established that major thrust faults do produce reflections. Across the Southern Appalachians, COCORP traced the Blue Ridge and Brevard fault zones at an angle of about 20° down from surface (where they are identified as thrusts) to a depth of around 9 km where they level off and merge into a near-horizontal detachment, dipping gently to the east and continuous for 450 km (fig. 2). Their demonstration (Cook *et al.,* 1979) that the major part of the metamorphic belt is allochthonous transformed the geological interpretation of the crustal evolution of the region. COCORP's profile across the Green River Basin in Wyoming (Smithson *et al.,* 1978) established its eastern margin, «the Wind River Uplift» to be an eastward dipping thrust fault, linear in vertical section traceable from surface effectively to the Moho (fig. 3).

BIRPS first profile shot in 1981, MOIST, offshore along the north coast of Scotland (Smythe *et al.,* 1982), discovered a number of features that have subsequently been found to be quite characteristic of the crust in Europe. A line drawing of the neighbouring DRUM profile illustrates them in figure 4. At surface a set of small basins containing Mesozoic and younger sediments are seen in section as wedges or half-graben in which stratal reflections dip west but terminate abruptly. The terminations are interpreted as near-vertical faults with downthrow to the east, controlling the basin development. Below and contiguous with these inferred faults, can be observed reflectors dipping eastwards at about 25° but levelling off at mid-crustal depths. Towards the western end of the profile, however, one particularly prominent easterly dipping reflector (or rather a narrow zone of dipping reflection segments) is traceable from sea bed to near the base of the crust. This reflector has been followed on other seismic lines in the area and correlates directly with the surface trace of the Outer Isles Thrust known on the island of Lewis to the south, which has been recognised as a major thrust fault active during the Caledonian Orogeny. The appearance of this reflector on the MOIST profile, bounding the Mesozoic basin that rests on its hanging wall, clearly shows the thrust to have been later reactivated as a normal fault. At around 9 s TWT a prominent subhorizontal package of reflections is observed along almost the entire length of the MOIST profile. This was identified with the Moho, known from an intersecting seismic refraction profile, and was the fist clear indication of normal-incidence reflections from the crust /mantle boundary. The most surprising discovery of MOIST, however, was the presence of an easterly dipping package of reflectors at the western end of the profile within the upper mantle and extending into the lower crust, possibly displacing the Moho. Although its origin remains obscure, its similarity in appearance to the Outer Isles Fault reflection zone suggests it may also represent a fault of some kind. Its reality has been established by further deep profiles in the region, one of which, DRUM, shot in 1984 (McGeary & Warner, 1985) and recorded to 30 s TWT allows it to be traced to at least 70 km depth (fig. 4). The DRUM line also found another strong, apparently sub-horizontal reflector at around 50 km depth within the upper mantle. So far it is only in this area that such strong reflections have been found within the upper mantle and experience will show how unusual these features might be.

BIRPS next survey in 1982, WINCH, was designed to cross the major lineaments associated with the Caledonian orogenic belt of northern Britain, including the Iapetus Suture, the inferred join between the two former continents of North America and Europe when they collided between 480 and 400 Ma ago.

Brewer *et al.* (1983) identified the Iapetus Suture with a boundary zone dipping north at about 20° through the crust with strongly reflective crust on its southern side compared with less reflective crust to the north. This pattern looks remarkably similar to that on a COCORP profile across the coastal plain of Georgia towards Florida (Nelson *et al.*, 1985) which has been identified as the Appalachian suture between «North American» and «African» basement and also to the DEKORP Line 4 (Dohr *et al.*, 1986) over the Variscan region of SE Germany as it crosses from the Moldanubian to the Saxothuringian Zone, another likely suture (fig. 5). Subsequently, Klemperer & Matthews (1987) have observed the Iapetus Suture more clearly on NECLINE, a profile shot in 1985 along the East Coast of Britain. Another BIRPS profile, SALT, across the North Sea Central Graben shot in 1982 along the line of an earlier detailed refraction experiment established the coincidence of the base of the lower crustal reflective zone with the Moho as determined conventionally (Barton *et al.*, 1984).

SWAT, a joint BIRPS & ECORS (1986) survey across the Celtic Sea and western Channel, was shot in 1983 to explore a region dominated by E-W Variscan structures, although ENE-WSW sedimentary basin trends across the Celtic Sea may have had Caledonian or earlier origins. The south dipping Variscan Thrust Front shows clearly on two profiles, SWAT 2 and SWAT 4 but is not present on SWAT 5 further west. On SWAT 4 (fig. 6) it is demonstrably reactivated as a normal fault with the Mesozoic North Celtic Sea Basin resting on its hanging wall. The fault dips from surface at about 20° but levels in mid crust to merge with the top of a well-defined lower crust reflective zone, and may or may not ramp down again to greater depth. Associated crustal extension can be deduced from an interpretation of bed length of the lowest reflectors in the North Celtic Sea Basin and the cross sectional area of the sediments contained therein. Using the balanced-section construction techniques described by Gibbs (1983) the extension above the mid-crustal fault detachment at 12 km depth is 30 % ($\beta = 1.3$).

Lower crustal reflectivity is more strongly developed on the SWAT survey lines than anywhere else and its cause has attracted much attention. The base of the zone is clearly defined and has been mapped as the Moho. Profiles across granite bodies known to be present in the upper crust show no reflections from their boundaries or their interior but the top of the lower crustal reflective zone beneath their surface outcrop appears to be higher than in adjacent areas (fig. 6; Matthews, 1987).

The lower crustal reflective zone varies laterally in character and thickness. This is perhaps best illustrated by the ECORS profile across the Paris Basin and north of France (fig. 7; Cazes *et al.*, 1986). The lower crust is strongly reflective with a well-defined Moho at its base beneath the Paris Basin covering the internal zone of the earlier Variscan fold belt. But the crust as a whole becomes unreflective further to the northeast where the Variscan crust is overthrust on to the London-Brabant Massif, the Variscan Thrust Front being identified with a shallow, gentle dipping decollement that reaches surface as the Midi Fault. Traced back beneath the Paris Basin, the decollement roots down to the reflective lower crust via a duplex of impricated thrust ramps. The ECORS North France profile includes magneto-telluric measurements which have defined zones of high electrical conductivity which correlate remarkably closely with the zones of strong seismic reflectors. A thin, high conductivity (the inverse of which, resistivity $\rho = 30$ ohm) coincides with the Midi Fault decollement between 8 and 10 km depth. a region of moderate conductivity ($\rho = 1000$ ohm - m) is associated with the mid-crustal reflectors of the thrust duplex (with higher conductivity showing along the strike direction than along dip) and a relatively high conductivity is present in the lower crust where it is strongly reflective ($\rho = 400$ ohm - m) compared with the non-reflective lower crust of the London-Brabant massif with low conductivity ($\rho = 6000$ ohm - m). This coincidence between seismic reflectivity and electrical conductivity has been observed elsewhere and has been discussed recently by Gough (1986). The pattern of lateral variation in the reflective character of the crust of northern France has been found to be just the same beneath the Basin and Range Province of western USA. Meissner & Wever (1986) have demonstrated the contrast in reflectivity between crust that has been tectonically disturbed relatively recently, with highly reflective lower crust, and cratonic shield or platform areas of crust that has remained undisturbed for a major part of the Earth's history, which display little or no reflectivity.

Klemperer (1987) has correlated the depth to the top of the lower crust reflective zone, and Wever & Meissner (1987) have correlated its

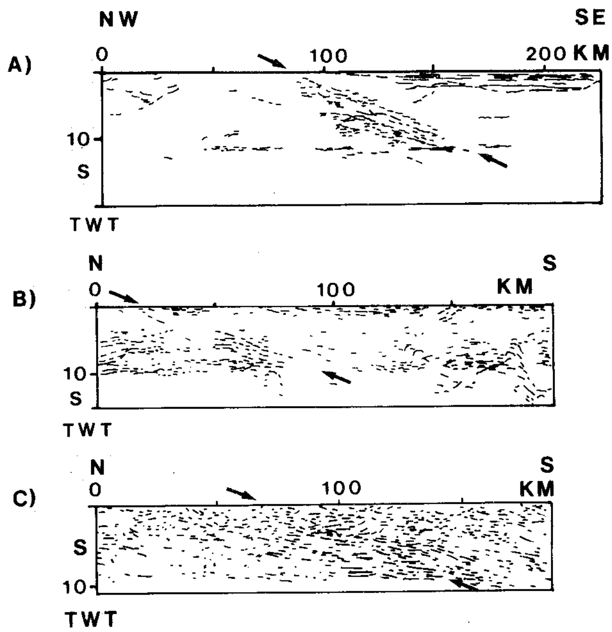

Figure 5.- Line drawings of deep seismic profiles illustrating possible sutures :
a) Southern Georgia, USA, COCORP Profile (after Broxn *et al.*, 1986); b) NECLINE Profile across lapetus Suture (after Klemperer & Matthews, 1987) along East Coast of Britain; c) DEKORP4 Profile across Erbendorf Line, central Germany (after Dohr *et al.*, 1986).

thickness, with heat flow, total crustal thickness and age. They have found that, in general the depth to the reflective zone and its thickness both increase as heat flow diminishes, and that in turn heat flow diminishes as crustal age and overall thickness increase. So it appears that reflectivity and heat flow are in some way related on about the same time scale. Since crustal heat flow anomalies take several tens of millions of years to dissipate, we may expect that seismic reflectivity of the lower crust may also dissipate on the same timescale.

Survey lines in West Germany undertaken by DEKORP have been directed across the Moldanubian and Saxothuringian Variscan Provinces of surface geology. Although dominated by Variscan structures, the area has been affected subsequently by Alpine deformation and the development of the Rhinegraben to the west. DEKORP Line 2S was begun in 1984 (DEKORP Research Group, 1985). The upper crust was found to be relatively free of reflections and the lower crust moderately reflective with a dominance of diffractions rather than sub-horizontal reflection segements. The profile has been interpreted (as shown in fig. 8) in terms of a crust that developed through thrusting along deep seated low angle faults anastomosing on a crustal scale, although the existence of overlying Mesozoic sedimentary basins points to some later extensional movement. DEKORP 4 further to the east shows similar features, with the Erbendorf Line that marks the surface expression of the boundary that separates the Moldanubian and Saxothuringian Zones showing the characteristics of a south-dipping suture (Dohr *et al.*, 1986; fig. 5). A N-S line in the Black Forest region completed in 1985 has a complex record section (Gajewski *et al*, 1987, fig. 9) including highly reflective lower crust which correlates with velocity features of the crustal model derived from a wide-angle reflection profile along the same line. This may also be interpreted in terms of large-scale thrusting and lower crustal character may be influenced by the proximity of the Rhinegraben.

A noteable feature of the DEKORP lines has been the use of wide-angle and off-line recording to obtain additonal information (Bittner *et al.*, 1987), particularly in order to examine the nature of lower crustal reflectivity in three dimensions. Although all deep reflection groups have concentrated on producing long profiles to give dip sections across major crustal features as shown from surface geology, there has been a growing awareness that the interpretation of deep crustal features requires three-dimensional information. In the Oberpfalz area DEKORP has produced a survey grid of three NE-SW and four NW-SE lines ot provide 3-dimensional control.

More recently, collaborative work has resulted in the completion of deep reflection profiles across the Pyrenees from France to Spain and along several traverses across the Alps in Switzerland and from France to Italy. The Paris Basin line has been extended by BELCORP across the Brabant Massif in Belgium. Between Norway and Denmark, surveys in the Skagerrak have crossed the Sorgenfrei-Tornquist Zone and extend up to the Olso Graben. The various national programmes now have considerable momentum and will be continuing over the next few years with increasing attention being paid to solving particular geological problems and testing the variety of hypotheses that are now emerging to explain the character of the seismic sections and their rheological and tectonic implications.

3.- INTERPRETATION OF DEEP SEISMIC REFLECTIONS PROFILES

The recognition that the geometry and internal structure of sedimentary basins can be controlled by major, crust cutting faults which may have long horizontal detachments and link with others over hundreds or even thousands of km has had a profound effect on basin analysis, with major industrial implications. As examples, I cite the work of Allmendinger *et al.* (1983, 1986) and

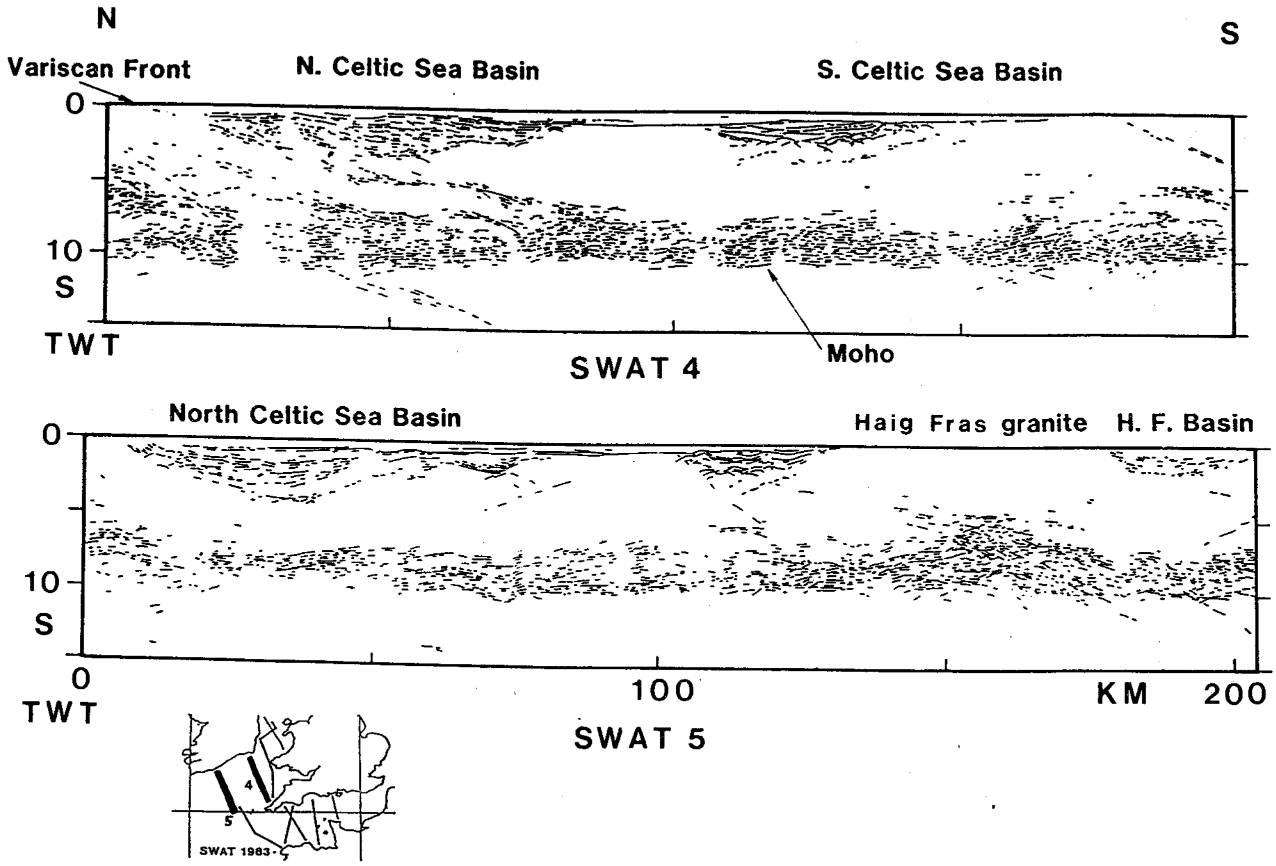

Figure 6.- Line drawings of SWAT Profiles 4 and 5 across the Celtic Sea (after BIRPS & ECORS, 1986).

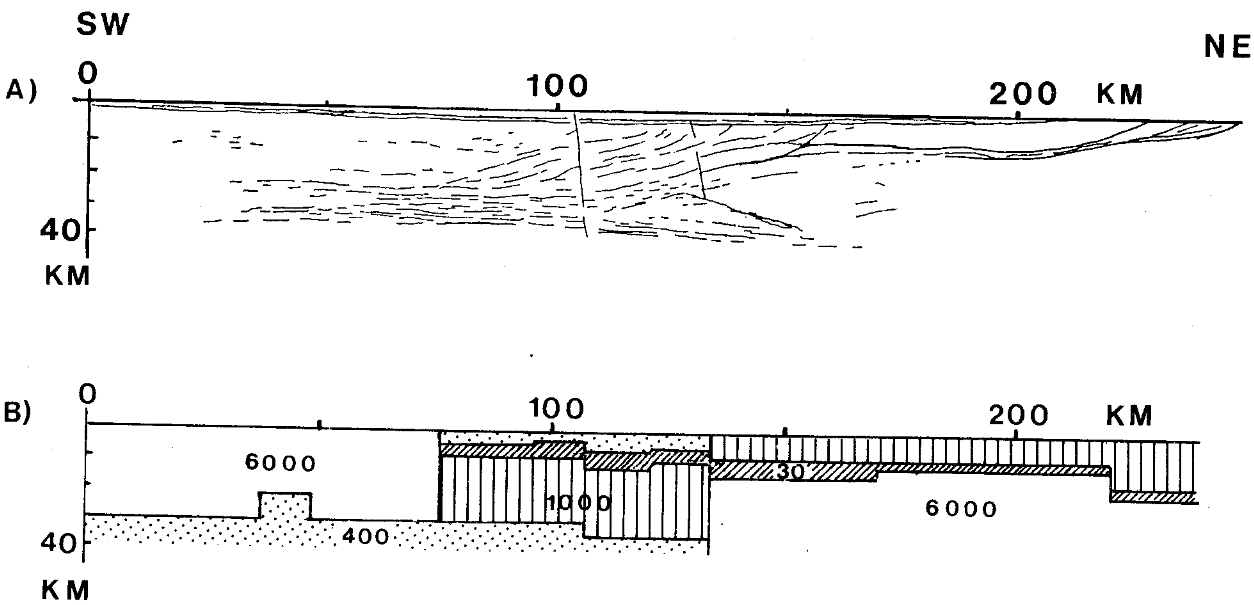

Figure 7.- ECORS North France line (after Cazes *et al.*, 1986).
a) line drawing of seismic section; b) model of electrical resistivity from magneto-telluric measurements. Values shown are in ohm-m

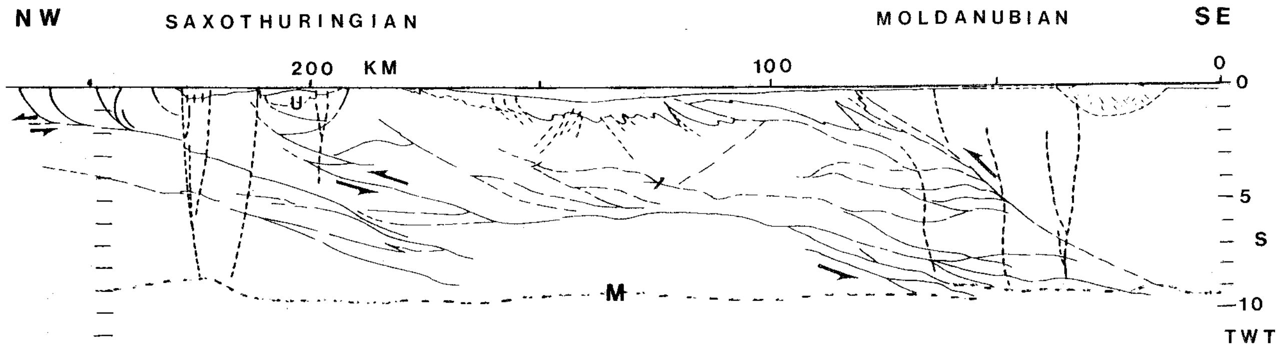

Figure 8.- Line drawing interpretation of deep reflection profile DEKORP 2S (after DEKORP Research Group 1985).

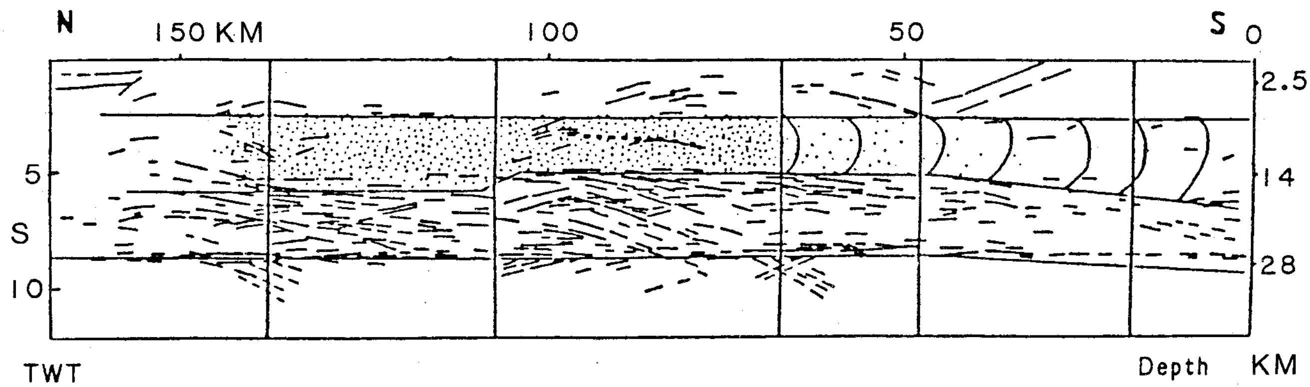

Figure 9.- Line drawing of deep reflection profile across the Black Forest superimposed on a velocity model determined from refraction and wide-angle reflection observations (after Gajewski *et al.*, 1987).

Smith & Bruhn (1984) on the Basin and Range, of Gibbs (1983), Wernicke (1985) and others in examining the geometrical implications. Beach (1986) has applied these ideas to interpret a profile across the North Sea Viking Graben (fig. 10) as an asymmetric rift in which a series of east dipping detachments link through the whole crust down to a shear zone in the mantle below the Horda Platform on the eastern flank of the rift. He explains the predominance on the western side of smaller rotated fault-block structures where the detachment level is relatively shallow in contrast to the larger blocks on the eastern side of the rift with steep linear antithetic faults bounding them reaching to a deeper detachment level. The size and nature of hydrocarbon accumulations relates to the scale and history (subsidence, rotation, slip, etc) of the blocks so that, if correct, his new interpretation has considerable commercial significance. However, his interpretation has been challenged by Klemperer (1988) who finds no evidence for faults cutting directly through the whole crust and on into the mantle. Instead, he views the lower crust as a more plastic zone in which bulk pure shear takes over from simple shear in the upper crust as the main response to stress, so that faults in the upper crust become decoupled from the mantle.

The faults themselves appear to have reactivated earlier structures although senses of movement may change. The inheritance of Variscan, Caledonian and older structures has been clearly recognised in the basins around Britain and the initial development of the basins appears to be strongly related tectonically to the immediately preceding orogenies. In the upper crust beneath the sedimentary cover, reflections are generally limited to narrow zones recognised as faults, whereas in the lower crust the reflective character is more broadly spread. This contrast has been related to a change in the rheology of the crust at depth from a more brittle upper crust to a more ductile lower crust, or possibly with intermediate zones of alternating ductility. In support of this idea, it has been noted that almost all earthquake activity in continental regions is confined to the upper crust or the mantle. Only in specific regions (eg. the northern edge of the Alps) are earthquake hypocentres found in the lower crust. Argument abounds as to the precise nature of this «ductility» but is is widely accepted that the reflectivity pattern indicates that strain is mainly localised in the

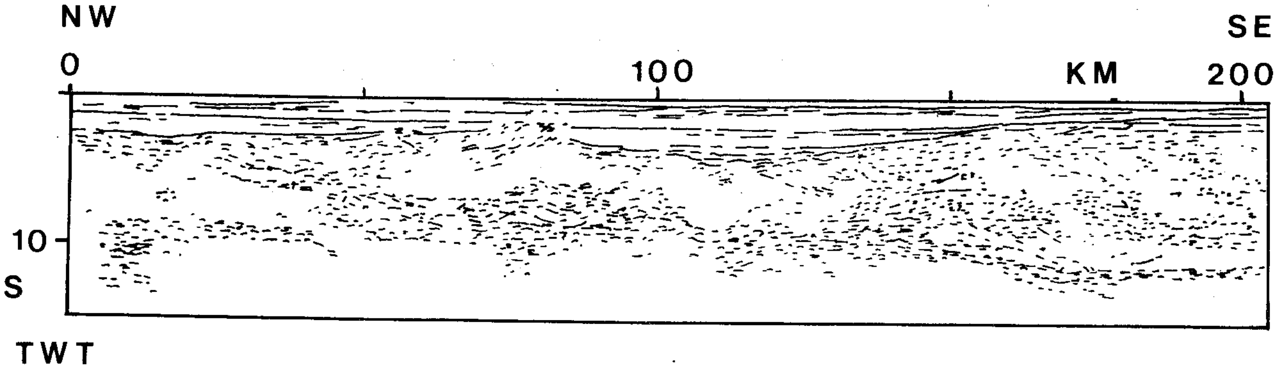

Figure 10.- Line drawing of deep reflection profile across the North Sea Viking Graben (after Beach, 1986).

upper crust to specific fault surfaces, the remaining volume of crust remaining undeformed (though possibly rotated and/or translated as blocks) whilst the strain in the lower crust is more perversive. The links between reflectivity, heat flow and crustal age and thickness imply that the upper crust has a long «memory» so that lines of weakness, once formed, remain so for a long time, whereas the causal features of lower crustal reflections may be relatively young, and relate to the most recent thermo-mechanical event to have affected the region. Thus old stable crustal blocks remain undeformed throughout whilst mobile blocks continue to react to stresses. The precise nature of lower crustal reflections is a matter of debate at present but most now accept that they generally represent the product of relatively recent deformational processes rather than relicts of ancient lithological contrasts.

A further line of evidence is the noteable contrast in crustal thickness between relatively young mountain belts such as the Alps which root down to 55 km or more and of older belts like the Caledonides or Variscides which have no roots : the majority of the area across Europe has crust uniformly of around 30 km (Meissner *et al.,* 1987). Moho topography appears to be preserved on small scales of less than 10 km wavelength or very large scales in excess of 1000 km wavelength (eg. the contrast in crustal thickness between Western Europe and the Baltic Shield and East European Platform across the tornquist-Tessyre zone from 30 km to greater than 45 km). Meissner & Kusznir (1986) have argued that the disappearance of crustal roots from beneath mountain chains (with ca. 100 km wavelength) comes about from ductile flow in the lower crust and upper mantle. They have prepared numerical models that realistically show the loss on a 100 Ma timescale of intermediate wavelength features of the Moho such as mountain roots but the preservation of short and long wavelength features. Regardless of the correctness of their model, the point is made that the disappearance of crustal roots from mountain belts implies a relative impermanence of lower crustal features. The change in reflection character and style of deformation between upper and lower crust implies lateral shear. Reston and I (Reton, 1987) have been modelling lower crustal reflectors and find that they can be explained through spacial interference effects, that is both lateral and vertical. The features giving rise to lower crustal reflections must be both laterally confined and close enough together to create the interference effects and we require a collection of lenticular shapes. Our modelling shows these to be elongated in the strike direction (of surface geology) to match with reflection character where we do have intersecting profiles giving three-dimensional control. We have proposed that these features arise from anastomosing shear zones deep in the crust within which simple shear can be quite narrowly confined and give rise to strong contrasts in acoustic impedence necessary to produce the seismic reflections. In addition to anastomosing shear zones magma has been recognised (Brown *et al.*, 1986) as a source of crustal reflections. Though strongly debated at present, the influence or presence of fluids within shear zones deep in the crust is favoured as a means of creating strong reflections and high electrical conductivity as well as contributing physically and chemically to movement along the shear zones (Gough, 1986 and comments on the paper by Yardley, 1986; Fyfe, 1986).

From studies of fluid inclusions in a wide variety of sedimentary and metamorphic rocks, Behr (1986) has recognised that two major fluid systems are present in the crust of Europe; one is a deep crustal system associated with Palaeozoic metamorphism that may have controlled Variscan thrust tectonics, whist the other is a post-Variscan system associated with sedimentary basin brines which has resulted in extensive hydrothermal mineralisation. The presence and extent of fluids and their association with fault systems and sedimentary basins has a major influence on the nature of the physical and chemical processes involved in crustal - and basin - evolution, so that a link with seismic reflections is of profound significance.

In summary, deep seismic reflection profiling can tell us how basin architecture is related to deep crustal structure and how the regional tectonic history determines the nature and development of the basins. It shows how crustal evolution is taking place and can be used to distinguish the deformational character of various crustal provinces and the sutures or boundaries between them. It relates to other geophysical observations of heat flow, gravity, magnetism, seismicity and electrical conductivity, and it relates to surface geology and regional structure shown on remote sensing imagery. Seismic reflection profiling has the highest resolution of all these methods but is most powerful when it is used in combination with them. On the larger scale deep seismic reflection profiling provides a high resolution image to combine with seismic tomography (Spakman, 1986) and wide-angle reflection/refraction experiments giving broad-scale lithosphere structure. On the smaller scale it acts as a framework to complement detailed seismic reflection surveys across basins for hydrocarbon and other resource exploration.

4.- PROPOSALS FOR A COORDINATED NETWORK OF DEEP REFLECTION PROFILES ACROSS EUROPE

I have proposed a network of profiles across Europe to fulfill the aims set out in section 1 as shown in figure 1. The first aim, to provide a network of long profiles across the major structural elements of western Europe, is met by the lines that traverse the whole continent. The north-south line from Denmark to Corsica follows closely the alignment of the European Geotraverse (Galson & Müller, 1986). The second aim to profile detailed sections of the crust and lithosphere that relate to geological and other geophysical data is met by the complete network. The third aim, to investigate sedimentary basins in a variety of tetonic settings, is met by particular profiles. Existing and planned profiles across the North Sea Viking and Central Graben and those west of Britain cover the predominantly extensional regimes of basin development. Existing and planned profiles cover the southern North Sea basin in which strike-slip movements are a major factor, but need to be augmented to cross certain elements, such as the Horn Graben to find out how their geometries are inter-related, and to link up with the Dutch Sector on shore. The Danish Sub-Basin and the North German basins offer the opportunity to investigate basement controls on salt tectonics. The Celtic Sea, English Channel, Weald and Paris Basins all have a history of Mesozoic development in transtensional regimes founded upon inherited Variscan basement structures which is followed by Tertiary inversion related to Alpine movements from the south. Although existing and planned profiles cross most of these basins, further profiles are needed to include the Weald and relate it to the Channel and Paris Basins.

The importance of overthrusting in basin development is being investigated across the classic Alpine Foredeep, the Molasse Basin, by a profile across Switzerland. However, a profile further to the east is proposed that would not only find out the extent of lateral variation along strike but would serve to connect the Molasse Basin with the Po Basin to the south of the Alpine core complex which has developed in a dominantly transpressional regime. The Po and Adriatic Basins developed in successively more complex transpressional stress regimes so that profiles across them would provide comparisons with the Molasse Basin and hopefully, contrasts with the northern North Sea basins. Further examples of a complex history would be provided by the Aquitaine Basin and Ebro Basin (and younger Tertiary basins peripheral to the Pyrenees) where Tertiary compression is superimposed on earlier extensional development.

Much of western and central Europe has been affected by Alpine deformation. Apart from the North Sea, the other area that has been relatively insulated from this deformation is the western side of the Iberian Peninsula, so that profiles there could be expected to show best the Variscan influence on subsequent basin development, without the later complications of Alpine movements.

Profiles across the Aegean basins provide the most exciting prospect for understanding processes of basin dynamics since these basins are actively deforming at present. Correlation between basement fault reflections and earthquake hypocentres and other indications of active tectonics could give the most direct evidence of the nature of the deformational processes and their connection with basin subsidence, sediment deposition and the growth of faults and folds within the basins.

Detailed reasoning in support of each of these profiles has been prepared to provide the case for a coordinated programme. It would require funding in the order of $ 50 million and would take about five years to accomplish. It could be regarded, perhaps as a successor to the European Geotraverse, to continue the highly sucessful level of collaboration that has been achieved under the auspices of the European Science Foundation. It would form a substantial component of scientific research into the Deep Geology of Europe, to complement deep drilling and associated research.

It would have, in addition, a valuable practical benefit. The sudden fall in the price of crude oil early in 1986 from around $ 30 to $ 8 a barrel had a devastating effect on oil exploration worldwide. Although the price has recovered to a more stable price at $ 18, European Community nations cannot afford to be subject to the vagaries of Middle East politics in this way. Exploration, in future, will have to be more cost-effective. Anstey (1986) has argued that the failure rate, on average, of five exploration wells in six to find oil can most effectively be reduced by an improved understanding of the geological mechanisms connecting source rocks, reservoir rocks and traps, and their timing. This is the direction of the proposals, so that the practical benefits of the research will be to provide a strategy for EC governments and industry to improve their assessment of indigenous resources, when used in conjunction with their own confidential data, and to make further exploration more cost-effective. I expect the research will indicate various geological settings to be prospective that are not currently regarded as such by industry. For example, good prospects for gas and oil lie beneath the Zechstein (Permian) salt which quite often forms the lowest level penetrated by conventional seismic surveys. In this case, exploration is largely based on the interpretation of surface and borehole geological information of the early development of the basin. This can be greatly improved by the geological understanding that comes from a knowledge of deep crustal structural controls shown on deep seismic reflection profiles, and the integration of geophysical and geological information into a dynamic basin model.

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