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SKETCH OF A POSSIBLE LINEAMENT PATTERN IN NORTHWEST EUROPE

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ABSTRACT

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Regional linear fracture zones, or "lineaments", are known to be elements of fundamental importance in the structure of the Variscan (Hercynian) and older basement in NW Europe. Several lineaments have shown periodic tectonic activity until very recent times; movements in different directions at different times are common. Based on data from various sources – especially aeromagnetics and Landsat images – the existence of several lineaments in the North Sea area is postulated. The known and the postulated lineaments can be loosely grouped into three recognisable, but not sharply defined, directional sets: around NW-SE, NE-SW, N-S. The effect of the lineaments on the structure of the Permian and younger cover is well expressed in the segmentation of the Mesozoic-Tertiary graben systems, in particular the Central Graben-Viking Graben.

INTRODUCTION

As part of Shell's project for collecting information on faults and fault patterns in northwest Europe, the overall tectonics of this region were reviewed, with emphasis on regional fracture phenomena. The review covered "transalpine" Europe, between the Irish Sea and the DDR/Polish border and northwards to approximately the 62° parallel. This includes the North Sea Basin – sensu lato – and parts of its frame where Palaeozoic and older basement outcrop.

In this region the folding ("alpinotype") tectonics of the Caledonian and Variscan (Hercynian) orogenic sequences came to an end in Late Carboniferous to Early Permian time. From then on the tectonic style is dominated by block-faulting ("germanotype") tectonics and epeirogenic basin formation. As a result, a major unconformity is found over most of the region with Permian (Rotliegend or Zechstein), or locally Upper Carboniferous, resting on more or less severely tectonised older rocks. For convenience, this unconformity will be referred to in this paper as the Saalian Unconformity (e.g. Knetsch, 1963; Heybroek, 1974; Ziegler, 1975). All older rocks will be taken together as "basement", the igneous/metamorphic part as "crystalline basement"; all younger formations are "cover".

Particularly in German literature, the tectonics of Central Europe are described in terms of a fundamental, large-scale mosaic of structural blocks acting as the controlling system of all Permian and younger geologic events (e.g. Knetsch, 1963). These blocks are separated by regional fracture zones, along which the blocks are relatively free to move with respect to each other. These boundary fractures are referred to in the literature under a variety of names, of which "lineament" has been chosen here as being the most distinctive.

In the following an attempt is made to establish the pattern of major lineaments in the basin frame and hence, by extrapolation, in the basin area proper.

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THE LINEAMENT CONCEPT

The term "lineament" requires definition because it is used in practice with different meanings.

O'L e a r y *et al.* (1976), after reviewing the history of the term in the American literature, propose to define a lineament as virtually any mappable linear feature on the surface of the Earth, regardless of dimensions, that "... presumably reflects a subsurface phenomenon". This definition has been especially adapted to include use in mapping from remote sensing data and the term is consequently used in this sense by, for instance, S e s ö r e n (1976) and F r o s t (this volume).

In European literature, however, the term "lineament" commonly has much more profound implications. W h i t t e n & B r o o k s (1972), in a recent dictionary, define it as: "A large-scale linear feature which expresses itself in terms of topography, which is itself an expression of the underlying structural features". M u r a w s k i (1972) in a German dictionary, sees the term as essentially synonymous with "Erdnaht" ('earth seam' of Cloos), paraphore, geosuture and geofracture. M o h r & P i l g e r (1969) after reviewing German usage, list five "characteristics" and ten "accompanying phenomena". M c C o n n e l l (1974), for example, uses "taphrogenic lineaments" for deep zones of disturbance in the lithosphere, fundamentally different from orogenic zones. W a t t e r s o n (1975) uses the term "lineaments" in the "European" sense in discussing a mechanism that will allow their development and maintenance.

Present consensus would appear to be in favour of a description for instance as follows: "A lineament is a zone of tectonic disturbance, which is straight or slightly curved, of regional dimensions (at least tens, and up to thousands, of kilometres long) and relatively narrow (a few kilometres at most). In many cases lineaments: are expressed at the surface by line-up of topographic features; have been active tectonically over long periods of geologic time, possibly from Precambrian to Recent; may reach down to the low-velocity, decoupling layer at the base of the lithosphere. Because of their nature as long-standing zones of weakness in the crust, lineaments may cause: facies and other palaeogeographic boundaries; changes of direction of faults, fold axes, etc.; ascent of volcanic material; concentration of ore bodies. In an unconsolidated overburden, lineaments commonly express themselves as line-ups of faults, narrow grabens, half grabens, synclinal depressions".

Additional characteristics will appear from the following description of "lineaments", recognised in the study area by their demonstration of the above features.

A difficulty remains, however: the definition does not provide any absolute distinguishing criterion and one is still faced with the question: where, going downward in the scale of dimensions, does one reach the limit between true lineaments and "ordinary", large faults or other fractures? The solution, as usual, has to be sought in making what appears to be a reasonable choice.

EXAMPLES OF LINEAMENTS

Basement areas (ref. Encl. 1)

In the areas of basement outcrop in the frame of the North Sea Basin, several structural features are found that correspond to the definitions of lineament; characteristics of a few of these may be briefly reviewed.

The most informative example is probably the Sillon Houiller (or "coal-bearing furrow") in the Massif Central of SE France (L e t o u r n e u r, 1953; G r o l i e r & L e t o u r n e u r, 1968). This is a zone of severe tectonic disturbance, mapped continuously over a length of some 230 km, running in a direction of about N 17° E overall. Its width varies from a few hundreds of metres to a few kilometres, within which several parallel zones of severe mylonitisation may be found. Locally, thin, steep plates of granite occur, either injected into the fracture zone as apophyses of adjacent granite massifs or torn off from these as tectonic shards. The zone separates different basement units over practically its entire length; these differences are at least in part the result of sinistral movements along the fault. These movements amount to some 50 – 70 km, according to various reconstructions.

Locally, the zone is covered by small, elongate basins with a Stephanian fill, partly coal-bearing (hence the name of the feature). These basins show signs of rather severe lateral compression, resulting in crumpled structures of the coal seams; locally, there is evidence of left-lateral movements. Most basins are limited on one or both sides by near-vertical, major faults with throws reported up to about 1000 m. As the fill of the basins unconformably overlies basement, the principal activity of the Sillon can be dated as at least pre-Stephanian; deformation of the basins themselves is partly synsedimentary and certainly pre-Permian. Erosion remnants of an Oligocene cover are aligned on the Sillon, suggesting some Tertiary activity. There are indications that a minor part of the Tertiary volcanic activity in the area made use of the Sillon fracture zone.

The Sillon Houiller is one element of the intricate fault pattern that pervades the Massif Central (cf. R o q u e s, 1971). It is of interest to note that the Sillon Houiller, although fairly straight overall, is in detail made up of elements of directions varying from N 10° E to N 35° E and that the bends occur where other faults either cross the Sillon or split off from it.

Viewed regionally, the Sillon Houiller occurs at the boundary between areas of different dominant strike of the Variscan and older structures: NW-SE in the area to the west as against NE-SW to the east. In French literature this is expressed as: the Sillon Houiller is the bisectrix of the "V-hercynien" (e.g. R u t t e n, 1969; D e b e l m a s, 1974). As regards post-Variscan events, it may be noted that the Tertiary graben formation (Limagne, Bresse) and volcanic activity, both very important phenomena to the east of the

Sillon, are virtually absent to the west, in the stable "Bouclier limousin" (L e t o u r n e u r, 1953). Moreover, P e r r i e r & R u e g g (1973) show that the Sillon is situated in – or may actually form – the transition between blocks of different crustal composition and Moho depth.

In summary, the Sillon Houiller shows the principal characteristics of a lineament and obviously has been a very important element in the tectonics of the region, from at least the later phases of the Variscan (Hercynian) orogeny to almost the present.

East of the Massif Central area, the Variscan fold belt continues towards Saxony-Bohemia. The dominant structural trend remains remarkably constant in the NE-SW ("Variscan" or "Erzgebirgian") direction until the vicinity of the Elbe River (near the city of Dresden) is reached (M ö b u s, 1964, 1966, 1968; P i e t s c h, 1955, 1962; S t i l l e, 1951). On the other side of the Elbe, the basement outcrop area of the Lausitz does not show such a clear dominant structural pattern; however, elements of Variscan origin and striking at right angles to the Variscan trend of the area to the west have been recognized; this suggests a major structural difference between the two areas. Moreover, the gneisses of the Erzgebirge to the west of the Elbe are believed to have been metamorphosed in the Assyntic phase (Late Precambrian); by contrast, stratigraphically equivalent graywackes in the Lausitz area are non-metamorphic. A further contrast between the areas is that the Devonian shows different facies development to either side of the Elbe river valley.

A well-defined structural element, called the Elbtalzone, (M ö b u s, 1964, 1966, 1968; P i e t s c h, 1955, 1962), separates these two geologically distinct blocks. This element can be observed over a length of some 60 km, running roughly NW-SE across the outcropping Variscan fold belt. Southeast of the town of Dresden, the zone is a 7 km wide belt of rocks of Algonkian to Carboniferous age, laterally compressed into isoclinal folds and bounded on both sides by steep reverse faults. More to the northwest the syenite/granite Meissen Massif was injected into the fracture zone. Smaller bodies of granite intruded along the western boundary fault.

The history of the Elbtalzone is summarised as follows. During the Late Precambrian orogenic events of the Assyntic phase, lateral, dextral movements of some 40 – 60 km are believed to have taken place. Isoclinal folding and thrust movements from the northeast marked the Variscan orogeny, with possibly some further right-lateral movements towards the end. Thereafter the Elbtalzone remained a zone of repeated subsidence. In the Rotliegend the coal-bearing basin of Döhlen (R e i c h e l, 1970) was formed and subjected shortly thereafter to minor folding, striking in the direction of the Elbtalzone; normal faults in the same trend also affect the basin, presumably caused by some Late Permian or Mesozoic phase of extension. In Mesozoic times the Elbtalzone tended to form a connecting channel between northern and southern seas. The Mesozoic deposits are to some extent overridden by the Lausitz basement block, upthrust along the eastern boundary fault, presumably in late Mesozoic. From the Tertiary some normal faulting, downthrowing to the east, is again reported.

Proceeding further counter-clockwise around the basin frame, the next area of interest is the crystalline basement complex in Scandinavia. Several more or less linear zones of obvious major tectonic importance are known from this area.

A striking feature is the zone of intense mylonitisation running over some 500 km in a roughly NNW-SSE direction through the Precambrian basement of south Sweden. Its tectonic importance is obvious from the fact that it separates two belts formed during different orogenic periods: Sveco-Fennides and Gothides (cf. R u t t e n, 1969). As no younger formations are present in the area, the subsequent history of the lineament cannot be established.

An outstanding element of Caledonian origin is the Central Trough in Norway, described as a fundamental feature by R a m b e r g *et al.* (this volume).

In Scotland the three well-known main fault zones can obviously be included in the lineament category.

The Great Glen Fault (J o h n s o n & F r o s t, this volume) stretches over some 150 km on the mainland of Scotland and probably extends over some 700 km or more in total. Johnson & Frost quote evidence that it "...separates different orogens – a Grenville belt to the north ..., and a Caledonian belt to the south". There seems to be fair consensus of opinion that important lateral movements (possibly over 100 km) have taken place along the fault; movement in different directions is not excluded. Mesozoic activity is reportedly well established and recent earthquakes show that the fault is not yet extinct.

The Highland Boundary Fault (J o h n s o n & F r o s t, this volume), is of Devonian or possibly older origin. It appears to have shown only dip-slip movements, in opposite directions at different times. No activity seems to have taken place after Carboniferous times. Substantial lateral movements are considered unlikely. Johnson & Frost's maps show clearly that the fault is, in fact, a complex zone of faulting.

The Southern Uplands Fault is described (Walton, *in* C r a i g, 1970) as a steep fault zone, consisting in fact of three segments, separate and slightly offset. Major downthrow to the north is concluded from Devonian palaeogeography and these movements were revived in the Carboniferous. Lateral components were probably also included in the "... long and varied history involving a number of movements".

The last basement area to be considered is the Massif Armoricain in Brittany. Here the outstanding lineament feature is the "Zone broyée sud-armoricaine", a complex fracture zone, several kilometres wide and visible over some 300 km in roughly NW-SE direction. It separates two blocks of different orogenic characteristics (Cogné, *in* D e b e l m a s, 1974): to the north lies an area of Late Precambrian basement with a folded but only slightly metamorphosed Palaeozoic cover; to the south both the Precambrian and the cover were involved in severe orogenic events of Variscan age. G r a i n d o r (1972) points out that the dominant basement strike is different on either side of the zone: NE-SW to the north and NW-SE to the south. The zone consists of various types of mylonitic rocks with granite intrusion plates. It is interpreted as a zone of severe lateral (roughly N-S) compression and probably major sinistral movements. The main intrusive activity is known to be of Dinantian to Westphalian age, but an older origin of the fracture zone is considered likely. In Stephanian time the Zone broyée became a zone of subsidence in which detritus – locally coal-bearing – was deposited in basins, which were compressed laterally shortly afterwards, quite similar to those of the Sillon Houiller.

Boundaries of basement blocks

The outer boundaries of the basement areas in the basin frame are locally formed by sharp, remarkably straight zones of surface faulting. As these fault zones separate basement from cover formations, they could be of post-Saalian origin. However, indications of Variscan or older age are also reported, suggesting that these features reflect old lineaments, revived as block boundaries.

A good example is the Fränkische Linie in southern Germany. To the east of this line is the basement area of Thuringia-Saxony-Bohemia. To the west is a block, mostly covered with relatively little disturbed Mesozoic deposits, called the Süddeutsche Grossscholle ("South German Main Block" – C a r l é, 1955); the Rhine Graben in the west and the Alpine Belt in the south form the other two sides of this large triangular block.

The Fränkische Linie is a complex NW-SE fault zone some 250 km long (C a r l é, 1955). The eastern (basement) block was uplifted over hundreds to thousands of metres with respect to the western block. Steep upthrust features, mostly dipping eastward, dominate, although extensional features are also reported. In detail, the zone is made up of elements in different directions: N 100 – 110°E, N 120 – 130°E and locally even N 170°E. It is believed that these directions represent old Variscan weakness planes "used as convenient" during the Mesozoic movements. The Mesozoic cover of the low block shows drag features and locally thrusting, in a relatively narrow belt adjoining the fault zone.

The Variscan area east of the Fränkische Linie is characterised by numerous NW-SE, transverse fault features (S c h w a n, 1957): Elbtalzone, Frankenwälder Querzone (S c h w a n, 1956), etc. C a r l é (1955) suggests that the Fränkische Linie was in Variscan times a similar transverse element, which was later "selected" to become a major block boundary. Farther to the southeast, the boundary is formed by the Bayerische Pfahl and the Donau Abbruch ("Danube Escarpment"); Carlé concludes from the fault configuration that the Variscan events must have included NW-ward, left-lateral movements of the eastern block with respects to the Süddeutsche Grossscholle. Tertiary variations in the stress patterns in this major block (W u n d e r l i c h, 1974) and their effects on the Rhinegraben (I l l i e s, this volume) suggest that the movement history, that started in or before the Variscan period, continued into very recent times.

The boundaries of the Massif Central in part show a similar character, although less pronounced. The southeast border, against the Rhône Valley, is formed by a system of parallel step faults; however, a complex fault zone, along which the bulk of the downthrow appears to have occurred, can be followed in a straight line over 150 km (C o u l e t, 1966). This Faille Cévenole (or "des Cévennes") is shown by Debelmas & Demarq (*in* D e b e l m a s, 1974) as a regional boundary feature, marked by sinistral movements. Similarly, the southwest border of the Massif against the Aquitaine Basin is formed by a fairly clearly expressed WNW-ESE trending fault zone; C o g n é *et al.* (1966) see this zone as a major left-lateral transcurrent fault ("décrochement"), probably related to the fault system of the Massif Armoricain to the northwest. The northern edge of the Massif runs slightly south of west from the vicinity of Moulins. M o n t j u v e n t & S a r r e t - R e y n o l d (1972) advance reasons to assume that this "remarkably straight" border represents a deep-seated fault feature: the "Accident nordcentralien"; B o l l o *et al.* (1976) support this suggestion on the basis of gravity data.

A very significant boundary is the Taunus Abbruch ("Taunus Escarpment") at which the Rhinegraben abuts northwards against the uplifted Rheinische Schiefergebirge. This fault zone was an outstanding feature already in the Variscan orogeny; it is part of the line separating the thoroughly folded, but only slightly metamorphosed, Rheno-Herzynikum to the north from the much more severely tectonised Saxo-Thuringian Zone to the south. Its importance in the Tertiary tectonics is obvious from the fact that the fundamental Rhinegraben rift stops against it.

The Rhinegraben itself does not conform to the definition of "lineament" (viz. width and lateral extension movements), but I l l i e s (this volume) concludes that the rift formed along a pre-existing weakness zone in the basement. It is noteworthy that this element apparently had much the same direction as the Sillon Houiller.

Mention should be made of a further lineament feature in this vicinity: the Schwäbische Lineament ("Swabian Lineament"). This is described (S e i b o l d, 1951; G e y e r & G w i n n e r, 1964) as a 140 km long zone of tectonic disturbance of the Mesozoic cover of the Süddeutsche Grossscholle. It is up to 4 km wide at the surface and variously expressed as grabens, half-grabens and unfaulted depressions. Seibold believes the feature to coincide with the important line separating areas of NW and SE vergence in the Variscan substratum, indicating the old origin of the lineament. Illies (*in* I l l i e s & F u c h s, 1974) points out that the Freiburg embayment, an eastern "salient" of the Rhinegraben, is situated where the lineament reaches the graben boundary. He also suggests that the lineament crosses the Rhinegraben and continues on the other side SW-wards in the zone of faulting that forms the northern boundary of the Limagne and Bresse Grabens. It is noteworthy that the character of the Rhinegraben is quite different south of this line from the parts farther north.

Attention should be given to what is perhaps the most important lineament of all: the so-called Tornquist Line (T o r n q u i s t, 1908). This is taken to form the southwestern border of the Fennoscandian or Baltic Shield and to run from Skåne (Scania, S. Sweden) SE-wards towards the Black Sea area. In Skåne the basement-cover contact is fairly well exposed and described (e.g. B e h r e n s, 1957/58; L i n d s t r ö m, 1967) as a complex field of faulting with individual faults trending in two somewhat different directions: roughly NE-SW and WNW-ESE. In N. Germany and Poland the basement border is covered by thick sediments and its exact configuration does not appear to be well established. It seems likely that the name Tornquist "Line" is something of a misnomer and that the line is, in fact, a wide complex fault zone as seen in Skåne. It would seem preferable to use the term "Fennoscandian Border Zone", as is often done in the literature.

Conclusion

The examples discussed above – although by no means a complete collection – may perhaps suffice to show that "lineaments", as defined, are indeed a common phenomenon in the frame areas of the North Sea Basin.

Although direct information on the nature of the crystalline basement in the basin area is scarce, there is little reason to believe that it is fundamentally different from that outcropping in the frame. Therefore, it is not unlikely that lineaments are also present in the basin area.

Several of the examples show tectonic activity until Tertiary or even Recent times. It seems possible that lineaments would have affected the structure of the cover and that, therefore, it might be feasible to recognise their presence in the basin area. The second part of this paper deals with an attempt to do so.

LINEAMENTS IN THE COVER AREAS

Expression in the cover

The post-Saalian cover is up to several thousand metres thick over much of the study region. The presence of a basement lineament must consequently be recognised through this thick cover. Unfortunately, information density decreases rapidly with depth below the surface. Conversely, the expression of the lineament in the structure of the overburden is likely to become fainter, going upwards from the basement surface (german literature uses the term "durchgepauste Tektonik", i.e. tectonics as it were "traced" through a stack of transparent sheets).

The expression in the cover is a matter of movements along lineaments in the basement affecting the structure of the cover. Even under idealised experimental conditions (planar basement fault, homogeneous cover), the resulting structures are by no means simple (H o r s f i e l d, this volume). In reality, moreover, many complicating factors are active: the lineament is not planar but has a decidedly finite width, within which several preferred movement planes may exist; these movements may be dip-slip, strike-slip or oblique; reversals of movement direction occur – inversion tectonics prevail over much of the region; the cover is by no means homogeneous – particularly in areas of thick (Zechstein) salt deposits, halokinesis leads to extremely complex structures (mobile clays may cause similar complexities); sedimentation is likely to go on while movements take place; etc.

Thus, a lineament may have quite different forms of expression at various levels in the cover and at various points along its length. Fortunately, the outstanding characteristic of lineaments should not be affected too severely by the complexities of the cover: *the linearity in inviolate.* Even if the structural effects in the cover should be spread out sideways by a few kilometres (in addition to the width in the basement), this is still small compared with the length of tens or hundreds of kilometres. Thus, recognition of the alignment of, even quite diverse, features on a straight line could well still be possible. The recognition process does, however, impose certain demands on the sources of information to be used.

Means of recognition

Required here is the recognition of linear features, tens to hundreds of kilometres long, probably several kilometres wide and more or less unevenly and vaguely expressed. It is understandable that this process will be facilitated by methods of investigation that yield an information grid of even density and quality over large areas.

This makes the oil industry's favourite data sources – wells and seismic – less attractive for the present purpose. Both tend to produce patchy information (except in very densely explored areas, such as North Germany and The Netherlands), requiring much interpretative mapping to fill in the gaps. Moreover, regional trends are often obscured by local "noise" produced by dense faulting, halokinesis, etc. Nevertheless, as will be seen below, effective use of such data has been possible occasionally, particularly in establishing palaeogeographic trends.

The most favourable geophysical method is obviously aeromagnetics, which, besides meeting the requirement stated above, has the advantage of principally reflecting basement structures. Unfortunately, in the deepest parts of the basin, the thick cover tends to even out contrasts and thus to make the survey results less informative. Gravity survey grids, although generally dense onshore, tend to be widespread and vague in the offshore. Nevertheless, this source has also yielded valuable information.

Relatively new is the use of satellite images (ERTS = Landsat). As each Landsat image covers an area 185 km square, with uniform conditions of illumination and image quality, this data source conforms ideally to the general requirement and has been used extensively in this study for land areas (Landsat images yield virtually no information over water). Only the most outstanding linear features seen on the images were traced onto the attached map.

Landsat images are frequently being used for lineaments analysis. Mostly, however, efforts are apparently being made in these applications to map every credible linear feature, regardless of dimension. This generally leads to maps showing dense grids of relatively short lineaments, i.e. in the "American" sense (O' Leary *et al.*, 1976). Examples are seen in Cavelier *et al.* (1974), Kronberg (1976), Sesören (1976), Johnson & Frost (this volume) and Frost (this volume). This approach is, of course, very useful if the results are to be used directly for purposes of detailed geological mapping.

For our purpose, however, efforts were made to map long straight, or almost straight, features, even if these showed discontinuities and vague parts. "Short" features, say less than 50 – 100 km, were generally disregarded. In order to reduce the risk of too imaginative interpretation, measures were taken to avoid bias: interpretation of individual images separately first, to be compiled into maps later; interpretation by two investigators (R.T.C. Frost and the author) independently; repetition of the interpretation after an interval of several months; comparison with geological maps only after the compilation maps were finalised.

The comparison of Landsat and published geological maps showed that in the areas of basement outcrop or thin cover, many Landsat linear features correspond to known fault trends. It is believed, as will be further discussed below, that also in areas of thicker cover or poor exposure, the linear features seen probably mostly represent fault lines. Mühlfeld (1976), working in the same area, discussed the ways in which underlying faults can find expression at the surface; his conclusions correspond closely to ours.

Once it was clear from the Landsat study that lineaments can be expressed by surface features, even through thick cover, it was a logical step to attempt the use of bathymetric maps of the North Sea area, where Landsat images provide no information. Some success appears to have been achieved.

In general, it was of course attempted to base the postulation of a lineament as much as possible on evidence from various data sources. This will be illustrated in the following regional discussions.

Eastern France – Southwest Germany

The area between the line of the Sillon Houiller and the Rhinegraben appears to be a good example of the use of Landsat images in the linking up of structural elements to form a likely lineament.

The Sillon Houiller loses its identity north of the Bassin de Noyant, from where the geological map (Carte Géologique de la France, 1 : 1 000 000, 1968) indicates a vague pattern of scattered fault features diverging northward. Landsat suggests that the most continuous and structurally the most important feature – as judged by the contrast between adjacent blocks in the frequency of linear features – runs in a fairly straight line slightly west of north from the vicinity of the Noyant Basin to that of Fontainebleau (SE of Paris). At this point it meets a clear Landsat lineament that runs ENE-wards through the eastern part of the Paris Basin to connect with the Faille de Metz, which itself is probably continuous with the Taunus Abbruch, leading to the northern end of the Rhinegraben. It seems significant that neither lineament continues beyond their meeting point.

Further south, a roughly parallel line-up of well expressed Landsat features coincides with the following structural elements (starting from the east): the Guebwiller salient on the Rhinegraben – faulting on the SW border of the Vosges – the boundary of the Tertiary of the Bresse Graben against the Mesozoic of the Paris Basin – a belt of Permian volcanics crossing the Morvan High in the trend of the line-up – the northern end of the Limagne Graben. Examination of Landsat images suggests that the lineament, after crossing the Sillon Houiller trend, may continue as the "Dislocation de la Marche", a major fault in the Massif Central (Grolier, 1971; Carte Géologique, 1968).

A roughly parallel, but a little more curved, alignment of Landsat and mapped features connects: the line where the Jura folds encroach upon the southern end of the Rhinegraben, a small Trias horst near Besançon, the Permian Blanzy Basin across the Morvan High and its continuation between the two branches of the Limagne Graben. From there the Landsat images are uninformative, but there is a likely continuation via a subsurface fault known from gravity and seismic measurements (Morange *et al.*, 1971), that obliquely crosses the Limagne Graben, and proceeds through the Faille de St. Sauves to join the Sillon Houiller at an acute angle.

North German Plains

In the west of this area, where the cover is thick and well explored, two Mesozoic tectonic phases are recognized. The movements of the earlier phase were reversed universally in the later phase, leading to complex tectonics. Boigk (1968), in describing these events for the Lower Saxony Basin, concludes that the movements took place along faults or flexures with NW-SE trend, which probably follow old lineaments. Two of these features may briefly described.

The remarkably straight course of the Aller River, in the easterly continuation of the reach of the Weser river on which Bremen is situated, coincides with a subsurface zone

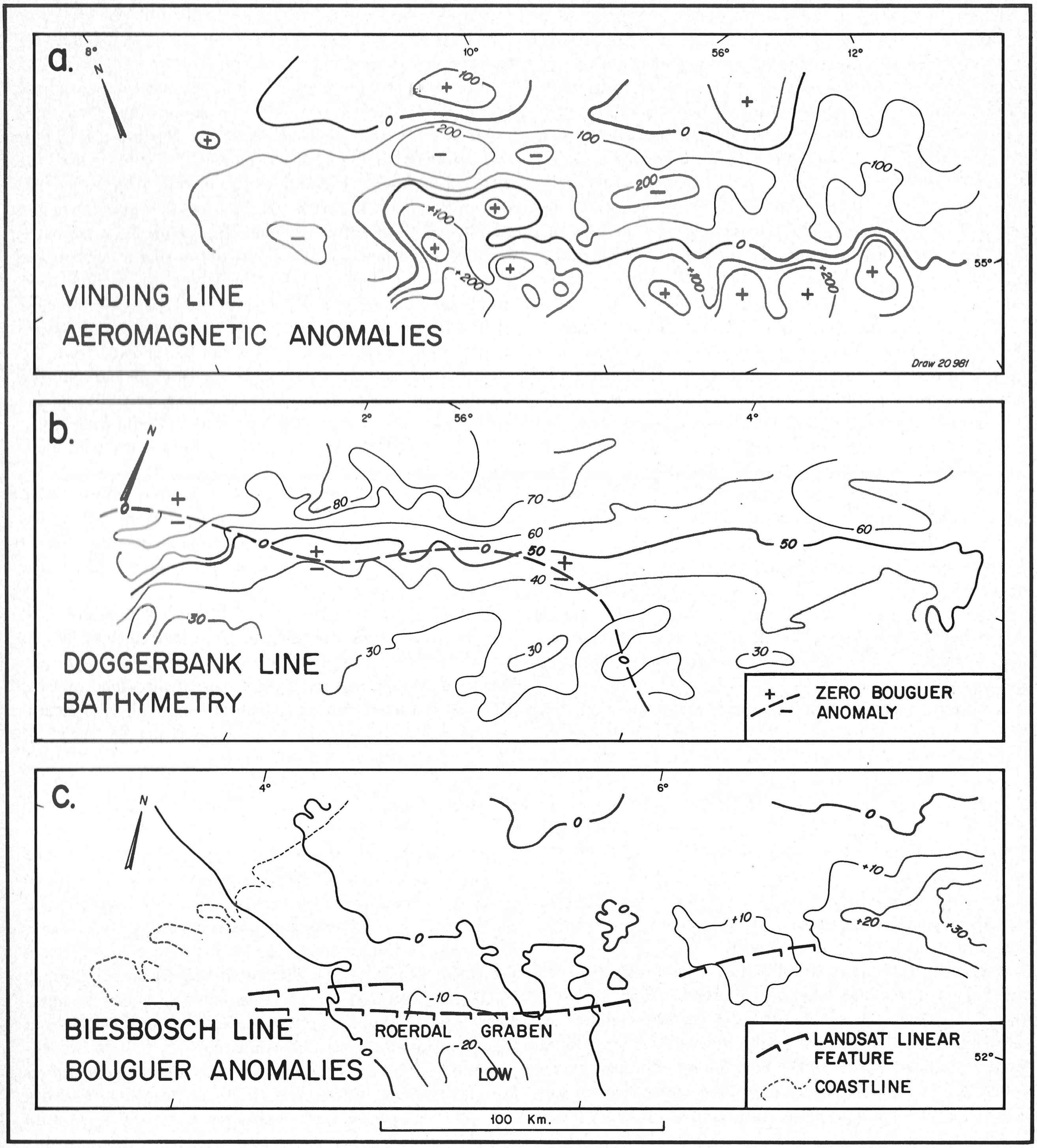

Fig. 1
Examples of the expression of lineaments.

of importance in the regional geology. This line is referred to in the literature as the Aller Line. Boigk (1968), for example, shows it as a pronounced boundary between areas of thin and thick Upper Cretaceous and as the NE basin edge in Valanginian time. On a map of the pre-Cretaceous surface by Nodop (1963), it stands out as an important feature. It is marked by an alignment of elongate salt structures, as can be seen on the map by Jaritz (1973); this line-up also continues to the west of Bremen. On the same trend Lutz *et al.*, (1976) show a hinge-line type of facies boundary in the Rotliegend and the shape of the isopachs farther west indicate that the lineament may extend well into the offshore area. As the Rotliegend lies directly on the Saalian unconformity plane, it seems likely that the hinge line, and thus probably the entire lineament, is of pre-Saalian origin.

The Aller Line is clearly expressed on the Landsat images, which also indicate a probable extension SE-wards towards the Flechtinger Höhenzug. This is a subsurface horst, elongate in the trend of the Aller Line, not unlike a small Harz. This brings the extended Aller Line to the vicinity of Magdeburg. This town is also often mentioned as the northwestern endpoint of a probable extension of the Elbtalzone (Stille, 1951; Kölbel, 1954; Pietsch, 1962; Möbus, 1966, 1968); Landsat supports the likely existence of such an extension. Similarly, the Elbtalzone is reported to extend to the other side, SE-wards into Czechoslovakia well past Prague; the satellite images also show this continuation. Thus a continuous lineament would appear to be defined, running over some 800 km from Bohemia to the North Sea with a slight change of direction at Magdeburg and possibly at Bremen.

A similar, clear Landsat lineament runs from Hamburg ESE-wards along the Lower Elbe river, then to Berlin and beyond almost up to the DDR/Polish border. This line is also marked by an alignment of elongate salt domes; to the WNW of Hamburg, a line-up of sigmoid bends in otherwise roughly N-S running salt ridges (Jaritz, 1973) suggests that the lineament may extend into the offshore. It also coincides with the SW border of the Ostelbische Massiv, a basement block which, according to Krebs (1975), is a striking positive magnetic anomaly and a gravity high, as well as an area of shallow Moho.

A further ESE continuation of this Hamburg-Berlin Line into Poland might also be expected from analogy with the Aller Line-Elbtal Zone. However, the Landsat pictures are unfortunately uninformative in this area. Roughly on trend lies the northeast border of the Fore-Sudetic Block (Znosko *et al.*, 1972) running south of the Oder River in the vicinity of Wroclaw (Breslau). According to Sokolowski (1970), this feature formed the coast line of the Rotliegend Basin, testifying to its probable Variscan or older age. It is clearly expressed on the Landsat images but these also suggest that it may continue NW-wards into a set of features going towards Magdeburg and thus possibly connecting with the Aller Line; Kölbel (1954) suggested such a possible connection as well.

Danish area

In this area, say between the Hamburg-Berlin Line and the subparallel Tornquist Line, the most interesting information is obtained from magnetic data.

The most striking feature is a trough of negative anomalies, in the order of 20 km wide and running over a length of some 300 km from Själland, along the North shore of Fyn and across Jutland (Fig. 1a, "Vinding Line"). Farther to the west the contrasts become less clear, but the feature may well continue on the same trend for another 200 km to the vicinity of the Central Graben. The feature is of probable tectonic importance as it follows the northern edge of the Fyn-Grindsted High, a well-defined block of shallow basement also trending in the Tornquist direction. The SW edge of this block is similarly marked by a line-up of "steep zones" on the magnetic map; this can be followed from the offshore, across the neck of Schleswig-Holstein and onto the mainland of the DDR where it becomes very clearly expressed. Again farther south the Hamburg-Berlin Line is also recognisable, albeit somewhat vaguely, as a magnetic boundary.

Summarizing this section and the previous section, there appears to be fair evidence defining a set of subparallel lineaments running from the Polish plains and the eastern part of Bohemia, WNW-wards until they apparently disappear in the central part of the North Sea.

A very peculiar feature in the magnetic pattern is a marked "steep zone" running in a direction slightly east of north from the vicinity of Bremen in a virtually straight line over some 300 km to the eastern part of the island of Fyn. The feature could not be related to any other geological element, except that its direction is closely parallel to that of the Sillon Houiller and the Rhinegraben.

The Netherlands

On Landsat images of the south-central part of the Netherlands, a straight line separates an area of low tonal contrast to the north from a much more patchy pattern in the south. On further investigation, linear elements were found on the images, indicating a continuous line-up from the North Sea coast near the Dutch/Belgian border through Nijmegen to a point NE of Osnabrück (Sesören's lineament map (1976) shows the western part of this line and some elements to the east of Arnhem).

The tectonic importance of this line is best illustrated on the gravity map, which shows that the pronounced gravity low of the Roerdal Graben disappears rapidly northward from the line (Fig. 1c). This is supported by other subsurface evidence, as compiled by Heybroek (1974), who shows that the Roerdal Graben loses its identity at the line, and also that there is a marked change from the dominant fault trend of the Lower Rhine Embayment to the south, to a rather more westerly trend in the West Netherlands Basin to the north. In addition, the line also meets, near its northeast end, with the NW end of another important structural feature: the upthrust belt of the Osning Zone and the adjacent high block to the north.

Geomorphologically, the line appears to be expressed by the course of the rivers Rhine and Meuse: issuing from the depression of the Lower Rhine Embayment, they swing westwards, start forming distributaries and continue seawards in a belt of some 20 km wide, accompanying the line on the north side. The direction of the line is also clearly reflected by the very straight – especially on the Landsat images – southern shore of the estuary reaches of Biesbosch, Hollands Diep, and Volkerak. Because of this relation, the line was, for convenience, called the Biesbosch Line.

North Sea area

The clear topographic expression of many lineaments suggested that the surface features accompanying a lineament in the offshore area might be strong enough to be visible on bathymetric maps. The outstanding feature encountered on such a map of the North Sea is the northern edge of Dogger Bank. This edge is surprisingly straight: over a length of some 260 km the 50 m isobath does not deviate from a straight line by more than 3 – 4 kilometres (Fig. 1b). It seems unlikely that such a long, straight feature could have been formed by some surface agent (ice, currents?), if the process were not somehow controlled by the presence of a linear structural feature in the subsurface.

This Dogger Bank Line also marks the northern end of a gravity low, similar to, but larger than, the Roerdal Graben low (Fig. 1b & c). Subsurface information, although not providing very close control, suggests that the line coincides with the boundary between two areas of different formations subcropping below the Saalian unconformity: Lower Carboniferous to the south and Old Red to the north. Also, the line may form the northern edge of an old high on which no Rotliegend was deposited. On the basis of sea-bottom configuration, the line is believed to extend – with two changes in direction – into the Skagerrak area.

Another rather abrupt deepening of the sea bottom – not dissimilar to the Dogger Bank edge but much less regular – occurs on a line between the vicinity of Aberdeen and that of Stavanger. It lies roughly in the continuation of the magnetic expression of the Highland Boundary Fault, which can be followed over some distance offshore. In the subsurface, the northern rim of the area with Zechstein salt appears to fall fairly accurately on this line. This possible lineament has been called the Forties Line, after the adjacent Long Forties area of the North Sea.

Segmentation of the graben system

From the foregoing the influence of lineaments on graben configuration is clear: Limagne, Bresse, Rhine and Roerdal Grabens all end northward against a lineament. Similar effects may therefore exist in the North Sea area.

On the enclosed map the approximate outline of the Central Graben-Viking Graben system is shown: as the graben boundaries are not simple faults and the subsurface information is not complete, the exact configuration cannot be shown. Fortunately, additional information can be derived from the configuration of the subsided Base Tertiary: the "axial line" of this trough-like basin proves to follow the graben trend closely (the contours on the map were derived by simple interpolation of well data points and may therefore be taken as virtually factual information).

The resulting picture of the graben system clearly shows the influence of the postulated lineaments. Major changes in direction of the graben system occur at the Dogger Bank and Forties Lines. Lateral offsets of the Graben also appear at these lines; from the occurrence of a similar offset, the existence of a further lineament some 100 km north of the Forties Line may be inferred. It appears that the southern end of the Central Graben lies on the extended Aller Line. The position and shape of the salients on the graben sides show the influence of the lineaments. Outside the graben trend proper, the shape of the contours also shows the effects of the presence of lineaments, e.g. in the Danish offshore.

In summary, although the Central Graben-Viking Graben system as a whole makes a fairly continuous, sinuous impression, there appears to be fair evidence that the system, in fact, consists of a series of graben segments. Features such as direction, width, depth of subsidence of Base Tertiary, vary from segment to segment. Each segment appears to lie within a structural block, the boundaries between these blocks being formed by lineaments.

Assuming that the graben system originated in response to an overall stress system applied to the whole region, it would appear that the geometry of the structural blocks and differences in their internal structure, caused local variations in the overall stress system and in the crustal reaction to these stresses. This then resulted in the segmentation of the graben.

Directions and mechanisms

Inspection of Encl. 1 shows that the lineaments are arranged in certain preferred directions; these may be termed NW-SE, NE-SW and N-S. However, closer inspection shows that the actual situation is rather more complex. For instance, the three sets of Landsat features that meet at Magdeburg, could individually be called NW-SE but, in fact, their directions are appreciably different. In the NE-SW direction, the same holds for the Southern Uplands Fault and its two, magnetically indicated, offshore branches. Also, an individual lineament, when examined in detail, tends to show considerable variations in direction between segments.

Therefore, such qualitative "eyeballed" directional classifications are dangerous. They may falsely suggest a significant degree of system in the arrangement of the lineaments. Words such as: parallel, orthogonal, conjugate, complementary, appear to be used rather loosely, which is particularly bad if they are made to carry genetic implications in terms of stress systems. It would appear that, although preferred directions undoubtedly exist, attempts at directional classification should wait till the lineament pattern is well enough defined to allow statistical analysis.

Lineaments may be of very fundamental tectonic importance. They are variously reported as boundaries between areas of different:

orogenic phase	–	e.g. Great Glen Fault
orogenic intensity	–	e.g. Zone broyée, Taunus Abbruch
crustal composition	–	e.g. Sillon Houiller
Moho depth	–	e.g. Hamburg-Berlin Line.

Nevertheless in recent literature little information was found on the mechanism or mechanisms by which such fundamental elements of crustal structure could have been created. It seems important that the majority of these elements appear to have originated during violent orogenic events which, moreover, can have occurred at any time from Precambrian to Carboniferous. As these orogenic processes could presumably vary with time and circumstances and do not appear to be fully understood in many instances, questions regarding the mechanism forming lineaments, or a particular lineament, should perhaps remain unanswered for the time being. Meanwhile, care should be exercised in applying genetic terms such as shear zone, subduction zone, etc.

CONCLUSIONS

Lineaments, in the sense of regional, old, deep and linear fracture zones in the crust, are a common feature in the areas of basement outcrop in the frame of the North Sea Basin. Several of them can be shown to have played a fundamental part in the orogenic events that produced the basement structure. In several instances post-Saalian (i.e. approximately post-Carboniferous) to very recent tectonic activity has been observed.

There is little reason to assume that the basement underlying the North Sea Basin area is essentially different from that outcropping in the frame. Hence, it seems likely that lineaments exist in this area as well and have affected the structure of the Permian and younger cover. By examination of information from various sources – magnetics, gravity, palaeogeography (from well data), satellite images and bathymetrics – a number of possible lineaments occurring in the basin area were recognised.

The known and the postulated lineaments together form a pattern that extends over much of the study region. The grid shows three dominant directions of lineaments: roughly NW-SE, NE-SW and N-S; the directional sets are not sharply defined, however. The effect of the lineaments on the structure of the cover is particularly well expressed in the segmentation of the graben system: segments of consistent trend, width, etc. stretch from lineament to lineament across major structural blocks, but these characteristics vary across lineaments. There are indications that the fault patterns also vary from block to block.

Although, admittedly, the supporting evidence is tenuous in part, the existence and tectonic importance of lineaments in NW Europe appear fairly convincingly established. It should be emphasized, however, that the lineament pattern as shown is no doubt incomplete and probably partly incorrect. It is hoped that – if the lineament concept is accepted and applied by geologists working in the region of study – it will be possible to complete and more clearly define the grid as geological knowledge of the North Sea area improves.

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