Geology. — *Lateral movements on the Alpine Foreland of Northwestern Europe.* By W. A. J. M. VAN WATERSCHOOT VAN DER GRACHT.

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It becomes ever more apparent that the major inter-continental orogenies of the world must be considered as the result of *unilateral* push, caused by one major continental unit of the crust encroaching upon another, in the sense of ARGAND, F. E. SUESS and others. Large continental blocks must be conceived as being laterally displaced, notably during certain worldwide periods of crustal unrest. The result is usually that the edge of one block is overridden (but occasionally also underthrust) by the edge of the encroaching unit, with duplication, or at least considerable thickening of the crystalline crust. This blocks the outflow of internal heat, increasing the geotherms, and simultaneously causes intense crushing of the inter-continental sedimentary mantle (the geosyncline) beneath the overriding masses. Minor backfolding is frequently in evidence at the rear of the orogenetic structure (Alpine Dinarides, Variscan back-folding and slicing in the southern Schwarzwald and the Vosges Mountains and in southern Moldanubia).

The character of the resultant more or less intense regional metamorphism of the rocks involved may serve as a help to unravel the usually very complicated mechanism. Kata-metamorphism is generally confined to the crystalline basement (not necessarily pre-Cambrian) of the blocks involved; it is not a result of the tectogenetic diastrophism, although in the enorogenetic zone kinetic metamorphism may have reworked the physico-chemical structure of the rocks entirely.

On the overriding elevated block erosion has frequently deeply bared these kata-metamorphic horizons; they occasionally also appear on elevated massifs piercing the sedimentary mantle of the autochtonous foreland, or in erosional windows of the frontal thrustsheets. The intra-orogenetic zone of intensily deformed sediments of the geosynclinal substratum under the overriding block is usually in the meso- or epi-metamorphic phase, but may occasionally contain kata-metamorphic rocks of the substructural basement, which may or may not have been subjected to retrograde metamorphism and turned into meso- or even epi-crystalline aggregates. Such poly-metamorphism frequently complicates the picture (**11**).

The major crustal overthrust (basement thrustplane — "charriage de fond" of ARGAND) evidently descends into unexpectedly considerable depths, as is proven by deep-focus earthquakes of the intermediate class (depths from 70 to 250 km), the epicenters of which invariably fall on or close to the major tectonic lines of Tertiary or more recent orogenies, in parallelism to the lines of epicenters of normal high-focus shocks, the deep intermediate foci being farther back of the mountain front than the

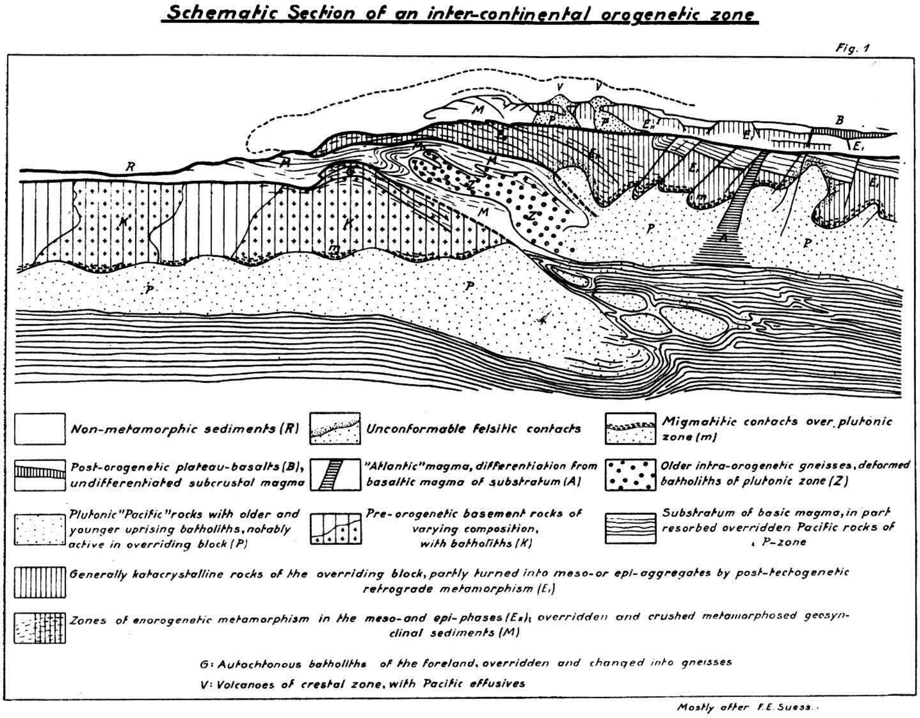

Fig. 1.

shallow shocks. The deep-focus earthquakes, as far as we know (meaning shocks at depths of 300—650, but not exceeding 700 km), are confined to the circum-Pacific ring and must have a different cause, scarcely connected with normal orogenetic stresses. Anyhow, therefor, the normal crustal disturbance of major orogenies apparently descends to depths of at least up to 250 km (East-Indies, Caribbean, Andes) (**6**). SMIT SIBINGA even asserts that in the Netherlands East Indies, therefor within the Pacific ring, even the deep foci remarkably coincide with the major orogenetic lines, as indicated by the gravitational work of VENING MEINESZ and morphologic discontinuities. Consequently, in the circum-Pacific region, orogenetic structure may even descend into depths of up to 600 km. (**8**)

That such intense interaction of drifting crustal masses of continental magnitude cannot have affected only the boundary zones of the colliding blocks, causing the major inter-continental mountain belts, is evident. The interior of the continents (the foreland) has also become warped, dislocated, and contains minor, but yet often important, intra-continental orogenies, but regional enorogenetic metamorphism has rarely been caused by such movements. It is admitted that it is not easy to explain exactly in which manner these stresses have been transmitted over long distances in an always more or less labile crust. Only it is evident from a concurrence of numerous observational facts, that pressure was active a long distance in front of the orogenetic belt, either by direct transmission through the actual crust, or by indirect action by way of still more labile subcrustal masses, dragging the super-structure like a current carrying floating ice.

The continental blocks are far from homogeneous. They contain units of greater or lesser rigidity, positive basement or substructural massifs next to negative regions (shelves), subject to repeated depression into basins and sedimentary troughs. These latter are more easily subject to deformation through lateral compression between more rigid massifs. In part this multifareous behavior may be caused by batholithic masses in the deep basement, or it may be caused by older orogenetic structures of a former phase, now solidly incorporated in a continental crustal unit, but having retained a superior individual coherence and rigidity (substructural massifs). In a former treatise the writer has attempted to describe the structure of the Midcontinent Plateau of the North-American Continent, as caused by stresses originating from the major late-Paleozoic orogeny (Appalachian-Ouachita Mountains) along its outer border, an inter-continental branch of the worldwide Altaids (**12**). The present paper intends to analyse briefly some of the post-Paleozoic deformation of the continental mass of northwestern Europe, especially from the viewpoint of pressures affecting the continental block from the south, culminating into the Alpine orogeny on its southern rim, against the resistence in the north from the Fennoscandian nucleus. Next to this vise-action an independent westward tension is to be taken into account, originating from the opening Atlantic in the sense of WEGENER.

The European continental block shows a far more complicated mosaic of incongruous units than North-America. These have become compressed and jostled between the southern edge of the primeval Fennoscandic Shield and the northward pushing masses in front of the successive Variscan and Alpine diastrophisms. These two latest orogenetic cycles, however, and the pressures to which they subjected their respective forelands, are not the only cause of the deformation of the Northwest-European continent. All of northwestern Europe is traversed by a widespread major system of great WNW to NW trending lines of dislocations (lines of KARPINSKY), paralleling the southwestern rim of the Russian Plateau (from Galicia, Bromberg, Bornholm to Skone). These dislocations, sometimes overthrust, are in evidence from the Black Sea to Eastern England and independently cross the Variscan arc. The resistence of the old Russian-Fennoscandian nucleus to the Variscan and Alpine pressures from the south may be in a part the cause, the feature however, is of such magnitude that an underlying superior cause may be the explanation. The continent is also subject to still another, evidently entirely independent strain, in no way connected with the interaction between the European and Gondwana continental blocks, causing major N-S directed dislocations, originating particularly in the middle-Tertiary, although older similarly directed lines of weakness are indicated. These express themselves as *rifts* of a similar nature as those which disrupt the African continent; they must be regarded as a result of stretching by the same major crustal drifting that opened the North-Atlantic.

The Alpides entirely overwhelm the older Variscan arc in the east of Europe, approaching the Russian Plateau along the Dniester river in Poland. Farther to the west the Alpine foreland embraces an ever widening expanse of territory, which had previously been subjected to the Variscan revolution. In southwestern Europe the foreland is divided by the intra-continental Pyrrenean orogeny. The also Variscan Paleozoic substructure of Iberia, south of the Pyrrenees, is left out of the scope of the present paper.

The morphology of the Alpine foreland, as we know it at present, is a relatively recent development; the present topography is even of extremely late origin. The entire area is generally characterized by more or less rigid tilted blocks, sliding over or under and past each other, under stresses acting on them from the south, deforming the sedimentary filling within intervening downwarped basins, whilst the elevated massifs often show the Paleozoic substructure on their surface bared by erosion. These jostling "epirophoretic" movements, comparable to those in drifting ice-floes, originated in the middle-Mesozoic (Jurassic), they culminated in the late-Cretaceous and had another active phase in the middle-Tertiary, gradually subsiding but still noticeable in the Pleistocene and probably not yet extinct. The general lines of deformation are clearly outlined on the map of figure 2, after von SEIDLITZ (**7**). The relatively more rigid exposed massifs, remnants of the Variscan basement, are shaded.

Many of these dislocations and fractures, which indiscriminately disrupt even such old kata-metamorphic massifs as those of the Moldanubian zone of the Variscan orogeny, are revivals of the older Paleozoic, or even a more ancient pattern. As instances might be mentioned the repeatedly reactivated great quartz lodes of the Bohemian and Bavarian "Pfahl"s and the overthrust of the Lausitz granite massif over upper-Cretaceous. The "Frankische Brüche" bordering the Bohemian massif on the west, and the great thrustfaults on its southern rim over the Basin of the Danube are similar instances. In the interior of the Bohemian massif the faults between Eger and Bodenbach, and some others, were sufficiently deep fractures that they opened the way for sub-crustal basic basalts; they also cause a number of famous hot springs (Karlsbad and many others). The many transverse faults of the Variscan arcs were reactivated in the Jurassic and again in the late-Cretaceous; locally the movements restarted in the later-Tertiary and even in the Pleistocene. The basins

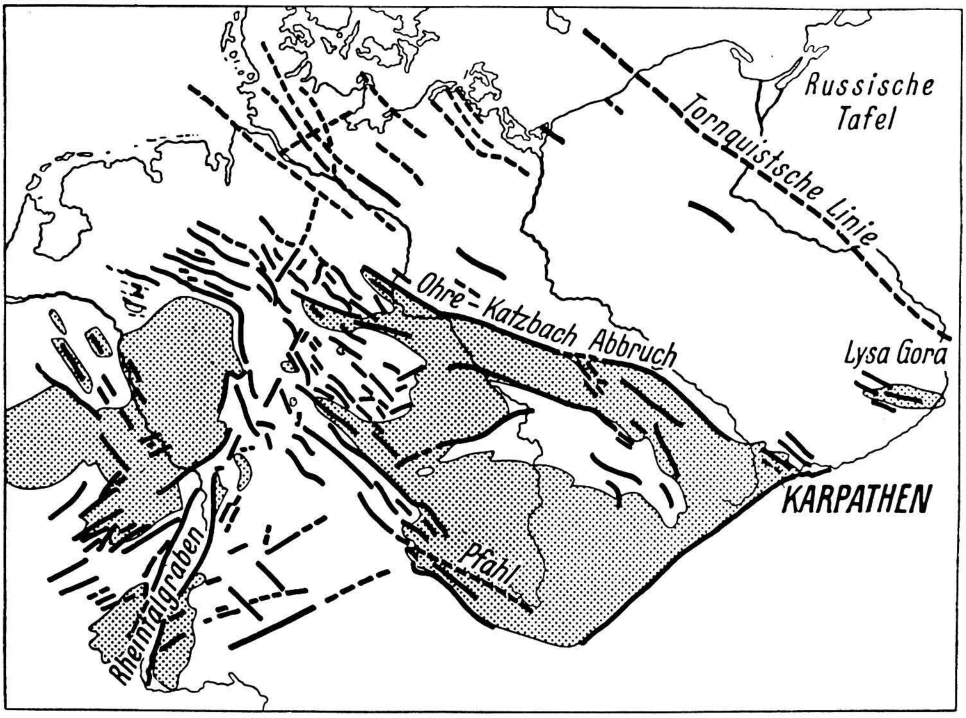

Fig. 2. Lines of Mesozoic (Saxonic) deformation. After V. SEIDLITZ, e. al.

between the positive blocks originated or were deepened also late in the Jurassic; they were compressed and folded principally in late-Cretaceous time. The salt domes of the deep basin of the northwestern plains show the same phases in the uprising of their saltplugs, proving that the same stresses continued to act on the subsurface that far to the north.

All these "Saxonic" movements show a distinct relation to the Alpine phases in the south, but they were not strictly contemporaneous. The following comparative Table shows them in juxtaposition. It is interesting to note that important warping and fracturing occurred on the foreland (Kimmeric phases) before notable deformation became apparent in the Alpine mountain belt. Presumably this was the time that deep in the crust the major inter-continental basement overthrust came into existence and placed the European foreland under considerable pressure, before serious deformation reached the surface in the actual Alps.

The scope of this paper does not permit to go into much further detail concerning the interesting movements on the many separate units which have been studied and described in the literature (4). It may suffice to review briefly the late-Mesozoic-Tertiary history of one of the major

OROGENIC PHASES IN ALPINE CHAINS	FORMATIONS	SAXONIC OROGENIC PHASES IN FORELAND
RHODANIC PHASE: second folding of Jura Mts, Molasse Basin and Sub-Alpine chains.	LEVANTIC	important regional changes of level on foreland blocks.
ATTIC PHASE: first major folding of Jura Mts. Molasse Basin (and Caucasus).	PONTIC	
	SARMATIC	
STYRIC PHASE: in Eastern Alps and Carpathians.	HELVETIC	MIOCENE PHASES: in numerous Basin-structures in western Germany and SE-England.
PYRRENEAN PHASE: major folding of Pyrrenees.	LOWER-TERTIARY	(Continental rifting, chiefly in Oligocene).
LAMARIC PHASE.	SENONIAN	LAMARIC PHASE: reversion of creep. SUB-HERCYNIC PHASES:
	TURONIAN	northward creep of basement.
AUSTRIC PHASE: major initial phase in Alpide chains of Europe: Alps, Caucasus, Carpathians, Dinarides.	CENOMANIAN	
	LOWER-CRETACEOUS	marine transgressions.
		UPPER-KIMMERIC PHASE:
faint deformations in Alps.	JURASSIC	major initial phase of Basin structures.
		OLDER-KIMMERIC PHASE.

substructural units of Central Europe, the Rhenisch-Ardennic block (Rheinische Schiefergebirge and Ardennes), inclusive of the Hunsrück-Taunus, which belong to the frontal Variscan zone, and its interaction with the pre-Variscan foreland-block, the Brabant Massif, in the northwest, and the Central-German block (Mitteldeutsche Hauptscholle) in the east. The latter is a much more broken and differentiated unit, comprising the Erzgebirge in the southeast, and the spurs of the Thüringer Wald, the Harz and the Flechtinger Höhenzug, with its continuation in the Lusatische Schwelle in the northeast. Its northern half is broken by two deep labile basins: the Subhercynic Basin, between the Harz and the Flechtinger Zug, and the Basin of Thüringen, between Harz and Thüringer Wald, both with numerous complex interior structures. Present morphology is exclusively a result of Mesozoic-Tertiary deformation, which is practically independent from the Paleozoic Variscan structure. The tectonic lines of the map of figure 2 strongly suggest the general creep towards the north, complicated though it may be by the crossing NNE zone of west-European rifting.

The present outline of the Rhenish-Ardennes block dates from the old-Kimmeric phase, in the Lias, and to a greater extent than in the eastern block its form is controlled by tectonic lines, dating from the Variscan orogeny. The southern boundary coincides with the late-Variscan Saar-Selke trough, but the present scarp is a result of very late-Pliocene and Pleistocene uplift of the Hunsrück-Taunus ridge (250 m uplift in Plio-Pleistocene!). The deep-faulted Embayment of Cologne (Kölnische Bucht) and the related Neuwied Basin are a rejuvenation of an older line of weakness around the southeastern spur of the Brabant Massif, which expressed itself already in the Variscan structure (Eifel sigmoid) and again in Triassic time (Nassau straits). The N-S trend of the Rhine rift intermingles here with NW-crossfaults of Variscan origin, rejuvenated in Kimmeric time. The northern and eastern edges of the substructural Rhenisch block (Rheinische Schiefergebirge) are Kimmeric. In the Jurassic the already preexistent swell (the Zechstein sea never covered this block) differentiated more sharply from the now rapidly deepening Basin of Hannover. The Mesozoic shoreline (Niedersächsische Uferrand) became more pronounced. The Hessian depression deepened. Late in the Jurassic, by the upper-Kimmeric phase, the northward pointing rim of the massif became surrounded by a chain of fault-folds: the pre-Cretaceous Egge range, which extended into the, afterwards differentiated, Lippische Schwelle a little farther north (**9**). The Paleozoic substructure became involved into this folding and was uplifted all along the northeastern boundary of the original block, with detached frontal uplifts at Detmold and notably around Osnabrück; at the latter locality even now the Coalmeasures are exposed. West of Ibbenbühren the structures of this phase become much less distinct under the rapidly increasing cover of more recent sediments, but apparently the Kimmeric deformation now spreads considerably farther to the south. Around Winterswyk, in the Netherlands, similar faultblocks as we find in the Egge are elevated and bring Lias, Trias, Zechstein and even Coalmeasures close to the surface. Here the movements are in part old-Kimmeric, as well as upper-Kimmeric. All through Twenthe we know similar, although not quite as highly uplifted blocks bordered by NW-striking faults. Positive gravitational anomalies indicate the continuation of this NW to WNW striking zone of highs in the deeper subsurface all through the Province of Overyssel, as far as the shore of the Zuiderzee and southwestern Friesland (with a deep basin to the northeast).

The next episode was a very different one. Tectogenetic pressure temporarily comes to rest but, at the time of the widespread transgression of the upper-Cretaceous all over western Europe, a very deep upper-Cretaceous basin (Münsterbecken) develops over the nothern half of the Rhenish Massif, considerably deepening the already dishlike depression of the Paleozoic surface by the uplift of its northern boundary in the Egge chains and the Winterswyk-Twenthe blocks. Between Münster and Koesfeld the thickness of the upper-Cretaceous cover (complete from Cenomanian to upper-Senonian) reaches over 1500 m. No upper-Cretaceous at all was deposited over the eastern Netherlands as far north as Ootmarsum (Erkelenz-Swell). The Cretaceous cover entirely buried the already baseleveled Egge structures.

It was only during the Senonian, beginning in Emscher time, that the tectogenetic pressures were renewed and now became particularly active. A differentiated northward drift of the Paleozoic substructure now becomes particularly conspicuous. It was at this time that the Harz block and other ridges of the eastern "Hauptscholle" were uplifted, tilted to the south, and their elevated northern and northeastern edges overthrust towards the north. This is particularly well demonstrated for the northern edge of the Harz block (2000 m throw). The original gentle swell of the Harz carried a cover of Zechstein, Trias, Jura, Cenomanian and Turonian; it seems that the block did not even form a shoal in the Zechstein sea. An old-Tertiary (presumably Eocene) peneplain lies now at + 1000 m above ordnance datum. The Brocken granite stood out above it as a low hill of sôme 120 m. Off the northeastern rim of the block the Paleozoic platform lies now at — 2000 m, indicating an aggregate uplift, at least difference of level (exclusive of erosion on the Harz block itself), of 3000 m. In the area of Hannover the Paleozoic platform should lie at — 3000 to — 3500 m, a difference of an additional 1500 metres. The uplift of the Flechtinger Höhenzug was less important: the difference in level between the Paleozoic outcrops and the platform off the NE-rim is around 1300 m.

On the Rheinische Masse the northern edge of the substructural block, with its adhering boundary zone of the Kimmeric Egge structures, was thrust bodily under the newly uplifted chain of the Osning (Osning Ueberschiebung), over a distance of at least 2 km (as proven by erosional windows). (9)

In the Hessian depression, the now thoroughly labile Basin of Thüringen, and the Subhercynic Basin south of the Flechtinger Höhenzug, a number of structures were uplifted, greatly complicated by the plasticity of intercalated layers of rocksalt. The overthrust of the Osning may also be explained as an instance of salt tectonics. The Cretaceous cover of the Rheinische Masse contains no saline formations, but these set in in the Trias, immediately north of the Niedersächsische Uferrand. Where there is no saline intercalation, the Mesozoic mantle apparently adhered firmly to the north-moving substructure, abutted against and was thrust under the masses farther north, which had the resistence of the enormous mass of 8000—9000 metres of sediments of the North-German Basin behind them. In this underthrusting saline intercalations, notably in the Röt and the Muschelkalk, seem to have acted as a lubricated shearzone (LOTZE).

In the deeper parts of the Basin of Münster the massif itself began to yield to the stress. Late-Saxonic deformation encroaches upon the Rheinische Masse whereever the Cretaceous cover reaches sufficient thickness to induce lability in the formerly rigid substructure. Already in the neighbourhood of the city of Münster there is indication of a gentle WNW-striking fold in the Cretaceous (1). In this northern area some increased activity is also observable within the Cretaceous along the NW cross-faults of the Variscan structure, which farther south do not affect the Cretaceous. Especially west of a line over Recklinghausen and Haltern, and north of Hamborn-Gelsenkirchen, late-Saxonic deformation sets in, as described bij BREDDIN (2). The movement shows itself as a series of WNW-striking folds, which gradually gain in importance in a northwesterly direction. Towards the southeast these folds turn into faultfolds and faultblocks. In the course of this process a number of the older Kimmeric NW-crossfaults were reactivated and show considerable throw within the Cretaceous. They also show the peculiarity that the movement was temporarily reversed. The older Kimmeric movements along these faults caused horsts and graben in the Permo-Triassic, and a still increased throw in the Coalmeasures indicates that activity dated already from the Paleozoic Asturic phase. These older movements were apparently a result of crustal stretching in SW-NE direction, possibly connected with the convexity of the Variscan arc. In the Cretaceous, on the contrary, compression to the N and NE is in evidence: normal faults turn into upthrusts; the graben in the older formations now turn into Cretaceous horsts, and anticlinal folds overlie older synclines or fault-troughs, and vice-versa. It must be noted that this reversal of motion is contemporaneous with the underthrust of the Osning and the other mentioned indications of suddenly increased northward creep of the substructure.

Still a little farther to the north, in the direction of the uplifts under Winterswyk, these movements continue to increase in importance (Raesfelder Kreidehorst). South of the Winterswyk block E-W folds set in, also involving upper-Cretaceous. Similar structures pierce the recent covering at Ochtrup, Bentheim and Losser. The entire anticlinorium of the Teutoburgerwald is explained by this mechanism. Beyond the North Sea it repeats itself in he Wolds of Yorkshire. It must be assumed to have been far more active and to have caused intense deformation in the deep, and presumably increasingly labile subsurface of the Central Netherlands and the North Sea. (13)

North of the Piesberg axis in the Teutoburger Wald a fairly general regional dip continues towards the north in the cuestas of the Wiehen and Weser Gebirge. The last visibly exposed fold is the Rehburg axis, running across the Dümmer See, eastward towards the Weser and the Steinhuder lake. Kimmeric folding, however, is no longer in evidence on this axis, the only observable phase is Subhercynic (upper-Senonian unconformable over older Mesozoics); some further movement is indicated in the Miocene.

Still farther towards the north substructural movements are indicated, contemporaneous with the later-Saxonic phases, in the numerous salt-domes which dot the deep basin in Oldenburg. Periodic movements on the rising saline plugs prove that the same forces continue to be active in the deep subsurface. (**10, 7**)

When we look towards the southwest, in Limburg and the Belgian Campine, along the eastern and northern boundary of the Brabant Massif, the Subhercynic movements become gradually obscured and more uncertain. As far as the Belgian Campine has been explored under the thick Tertiary and Cretaceous cover, Carboniferous Coalmeasures overlie the Silurian and older platform in a gentle north-dipping monocline, which has not been disturbed in late-Cretaceous time. These conditions have been ascertained as far to the northwest as the Woensdrecht boring, in western Noord-Brabant near Bergen-op-Zoom. Nowhere in this western region a sharp northern Abbruch is indicated, a condition similar to that prevailing in England. It is only at the eastern end of the Brabant Massif, in Limburg, that sharp downfaulting is in evidence. Here we are in the northern extension of the now greatly increased depression of the Kölnische Bucht. Now an enormous Tertiary graben develops, which can be traced all through the central Netherlands as far as the seacoast in Noord-Holland. The graben is caused by enormous NW-faults, which are clearly a continuation of those of the Kölnische Bucht. Now they cause, already between Sittard and Roermond, a depression of several thousands of metres. On the western side of this graben zone the bordering faults deflect to the WNW and finally almost West and seem to follow the northern contour of the Brabant Massif in the north-eastern Campine. A strong gravitational low is indicated a little farther north, with the same trend. The NW-faults originated already in Variscan time, were revived by the Kimmeric and the Subhercynic phases, and became very active again in Pliocene and Pleistocene time. They are still moving as proven by the epicenters of frequent earthquakes. These faults show the same reversal of motion during the Subhercynic phase as those described for Westphalen.

In the eastern Campine we have a curious instance of a northward dipping flat thrustfault in the Coalmeasures. It was encountered in the workings of the Limbourg-Meuse colliery at Eysden. Here a N-30°-W striking thrustfault (Faille d'Eysdenbosch) has become proven over a distance of some 1400 m along the strike. The fault dips only 26° to the NE; the southward movement along its plane amounts to 200 m (**5**). Less important rolls and crushing of a related nature have been described for the coalseams in the Campine mines. This movement, in this abnormal direction, can only be explained as underthrusting and the effect of a northeastward creep in the Brabant substructure against the resistance of the deep sediment-filled basin of the Netherlands. The great border-fault Faille de Rothem, and probable further stepfaults succeeding it towards the north, bringing in Trias and Lias on the downthrown blocks, might constitute a kind of Abbruch. Whether any thrusting occurs in connection with these faults is unknown, but it would not be improbable that they dipped to the south. Not very much farther north Saxonic folding should begin to make an appearance in the deeply buried subsurface. It would seem however as if the main line of Saxonic disturbance should be traced much farther to the north and that the pre-Variscan Brabant mass, which already in Asturic time proved such an unyielding buttress, continued to intercept the pressures from the south.

Late-Pliocene and Pleistocene movements of an epeirogenetic character have caused the present topography of the Alpine foreland. These important changes of level are especially conspicuous in the region adjacent to the northern plains, but they occurred all over western Europe, including England. One of the most striking ones is the uplift of the barrier of the Hunsrück-Taunus across the course of the Rhine. Some uplift of the Taunus may have started in the Oligocene, cutting off marine communication from the north, but the upwarping of the Hunsrück and the Eifel culminated in the Pleistocene, forcing the Rhine to dig its 200 m deep canyon through the dam. Around the canyon between Bingen and Andernach upper-Pliocene gravels (Kieseloolithe) occur around 300 m above sealevel, and near Cologne at + 115 m. The recent lower terrace of the Rhine is at + 54 m at Andernach. Consequently there was a surelevation of the Hunsrück-Taunus of some 250 m since the Pliocene. An older-Tertiary peneplain on the Hunsrück, covered by presumably Oligocene gravels, occurs at + 600—700 m; in the Siegerland there is a peneplain of about the same elevation. The base of the upper-Cretaceous now lies at + 380 m at Aachen, but is uplifted to + 600 m on the immediately adjacent Hohe Venn block.

Farther west the Diestien (lowest Pliocene) lies at + 160—170 m at Calais and Ypres, but only at + 7 m at Antwerpen and at — 66 m at Woensdrecht, — 142 m. at Rosendaal, whilst a boring at Utrecht proves that it lies below — 365 m there.

In the Harz Mountains an old-Tertiary, possibly Eocene peneplain occurs now at + 1000 m. A lack of Tertiary sediments in the immediate vicinity does not permit further precision, but remnants of Tertiary in the Hessian depression suggest that a Tertiary sequence of about 1000 m has been eradicated there by erosion. It is very evident, therefor, that the foreland has become very severely warped in extremely recent, practically the present time.

The tectonic features which have been discussed are all the expression of the periodically pulsating northward pressure on the foreland from the encroaching continental block that caused the Alpine orogeny. Entirely independent from these structures an autonomous line of deep N—S fractures traverses the entire western portion of the European continent from the mouths of the Rhone in the south to — possibly — the Mjösen lake in Scandinavia. Part of these N—S to NNE lines are well indicated on the map of figure 2, but the complete event can be better brought forward on the more general tectonic map of figure 3.

It is characteristic of all these fractures that they cause more or less wide and deep N—S fault-troughs and that they originate in the middle-Tertiary, notably in the Oligocene, but they continue to sink through all or most of the upper-Tertiary, the Pleistocene, and even recent time. The structure is entirely independent from other tectonic lines that cross it. The graben are only rarely deflected around massifs, but mostly split them indiscriminately. They seem to follow, however, some older — possibly very old — lines of weakness in the same N—S trend (3). They are traversed and continue to be affected by uplift or depression of the blocks they cross, which do not seem to lose their coherence. The importance and depth of the fracturing are emphasized by the fact that the fissures descend into depths where they open passage to the subcrustal basaltic magma. Active late-Tertiary volcanism characterizes the rifts: the greatest outpourings of basic lava's of this part of Europe occur along these lines. Like in Africa, a rifting of this nature does not cause a single clean-cut fracture, but — at least the surface expression — is a rather complicated zig-zag system of faults, fault troughs and even uplifts. The latter occur almost regularly in the zones bordering the fault-troughs at either side. Sometimes the troughs are duplicated by other more or less parallel rents; a zone of median horsts is almost the rule. The fractures are usually clearest where the crystalline, or at least substructural basement they have split is exposed at the surface in massifs.

The principal rift begins at the mouths of the Rhone in the Camargue and at Cape d'Agde on the Mediterranean coast. Amongst other depressions it causes the Rhone Valley trough, which is partly obscured by the foothills of the Alps of Dauphiné and farther north by the inroad of the Jura Mountains; it was generally deformed together with the Molasse foredeep of the western Alps, structures which were, to a considerable extent, caused or reworked by the Pliocene phases of the Alpine orogeny, a long time after the mid-Tertiary opening of the rift. The general area of the southern development is comprised between the old Moldanubian block of the Cevennes and the Plateau Central in the west, and in the east the Monts Maures of Var and the autochtonous crystalline basement blocks of the western Alps, from the Mercantour and Belledonne to the Mont Blanc. A parallel line of important fissures a little farther west rents the heart of the kata-metamorphic massif of the

TERTIARY RIFTING IN WESTERN EUROPE

Fig. 3.

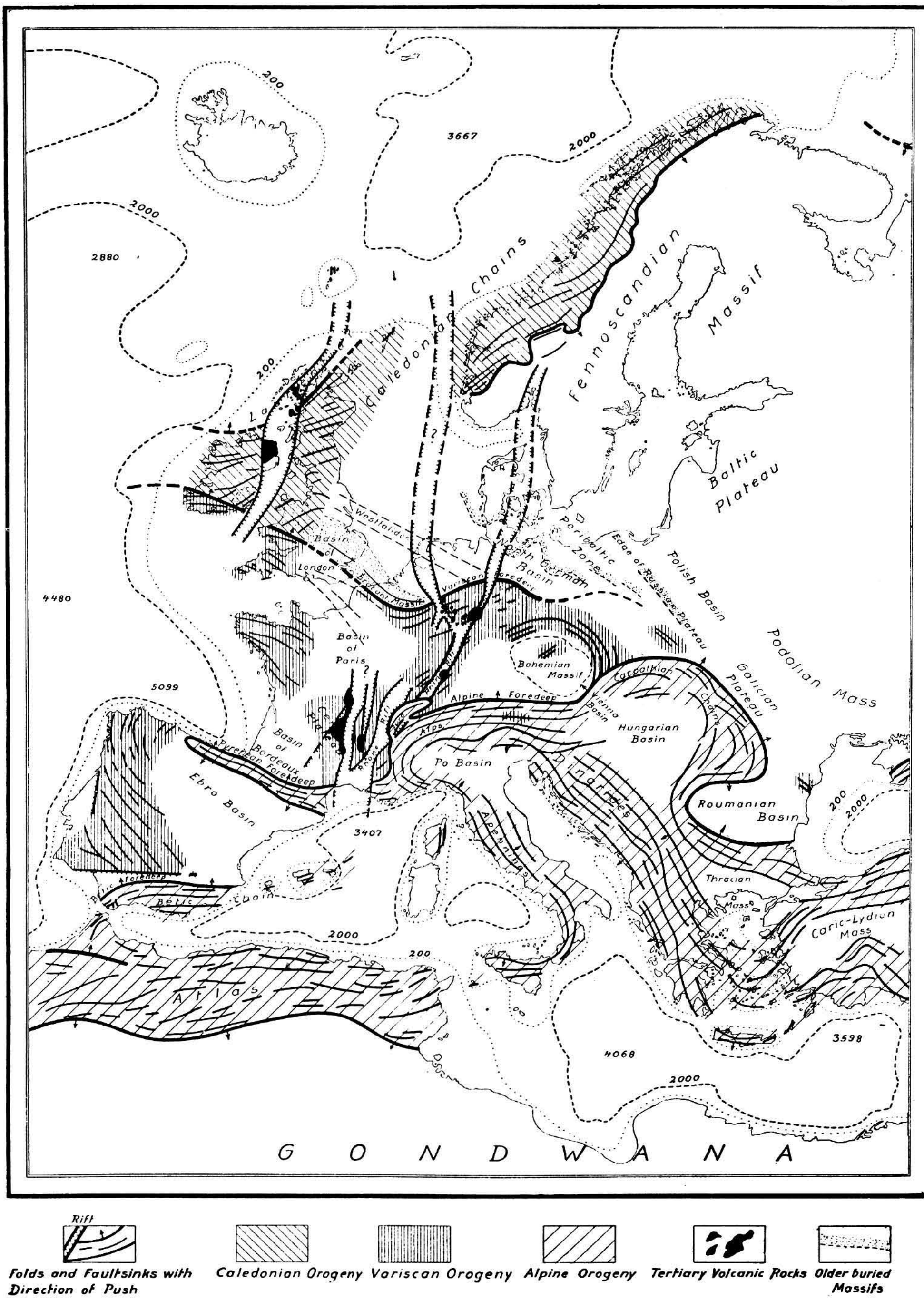

Fig. 3.

Plateau Central in the Loire faült-trough, and, more pronounced still, in the very deep depression of the Limagne, which is traceable in the sedimentary cover of the deep Basin of Paris as far north as Montargis, pointing in the direction of the deeper axis of the basin. A still more western fracture can be traced through the Plateau Central from along the Aveyron river and Villefranche, in an almost straight NNE direction, as far as Moulins in the Bourbonnais.

The Rhone Valley shows a maximum depression in the Oligocene, amounting to some 600 m. In the Miocene the bordering blocks, notably the Cevennes and the Beaujolais Mountains, were uplifted. The depth of the fault trough is not excessive, because in the transverse swell of Givors-Verpillière, borings easily reached the coalmeasures of the St. Étienne Basin, close to the Jura Mountains. In the Pliocene phases of the Alps the valley was uplifted instead of further depressed; in the region of Lyon the river had to cut a 60 metres deep channel.

The Rhone Valley lacks conspicuous volcanism. The rift of the Limagne, on the contrary, is a very deep chasm, where up to 1400 metres of Oligocene deposits are reported. The uplifting of the Auvergne set in during or shortly after the Miocene: an old-Miocene peneplain now lies at + 970 m. The great volcanism of the Puys reaches a maximum in the Pliocene, but the basalts of deep subcrustal origin are mainly Miocene. According to GLANGEAUD 1500 million cubic metres were ejected.

It seems a general characteristic that volcanism in these rifts becomes particularly active where they traverse old basement blocks; it becomes less conspicuous in labile depressions. It appears at the surface slightly later than the rifting.

In the north the Jura Mountains almost totally obscure the rift, but NNE-faults remain a conspicuous feature. Recent geophysical work in the Jura Mountains of Neuchâtel indicated the prevailence of tectonic lines in the same direction in the subsurface, crossing the NE trend of the Jura folds. This leads to where, between Belfort and Basel, the rift suddenly reappears in the great classic fault-trough of the Upper-Rhine Valley Graben.

The Upper-Rhine Valley possibly follows an old line of weakness suggested by Variscan shearing and Permo-Triassic depression. The region, however, was apparently unbroken in Jurassic and Cretaceous time, when it was simply part of the extensive high over southwestern Germany. The present rift dates from the Oligocene. In the middle-Oligocene the sea invaded the long and narrow trough both from the north and the south. The sinking was interrupted in the transition period between upper-Oligocene and Miocene, but became especially active again in upper-Pliocene—Pleistocene time. The bordering blocks were uplifted. The graben shows a certain asymmetry to the east: the most active faults were on the eastern rim; near Heidelberg they dip towards the mountain. Lateral shearing is indicated, suggesting a relative southward drift of the western rim. At Durlach, east of Karlsruhe, the depression is reported to amount to 3200 m (Jurassic at — 2400 m according to MOOS); 210 m would have gone down in the upper-Pliocene, 70 m in the Pleistocene. A zone of median horsts is indicated at many points in the graben, especially in the south.

Volcanism also appeared in upper-Miocene time (Kaiserstuhl basalt), and this again in an area where the rift split the formerly united block of the Vosges and the Schwarzwald.

In the north the deep fault trough is suddenly cut off sharply by the very recent uplift of the Hunsrück-Taunus ridge, but the rifting evidently continues across it in the depression of Hessen. It is most marked in the Leinethal Graben. The NNE-faults can be traced at many points through the northern plains and point towards a similarly directed trough in the Fennoscandian Shield at Oslo (the Mjösen fault-trough). The Mesozoic, and still more a Tertiary age of the trough north of Oslo is, however, uncertain. All we really know is, that there exists a N—S graben, containing lower-Permian, and possibly younger-Permian effusives, overlying Rotliegend. A much younger superstructure may have become wiped off by erosion on the rapidly rising Fennoscandian mass.

Although the rifting is less conspicuously expressed by subsidence in Hessen than in the Upper-Rhine Valley, deep fracturing of the crust is most evident. Where the rifting crosses the central-German blocks a very complicated structure results from the interference between Alpine *compression* towards the north, causing NW—SE block-folds and ridges, and E—W *stretching*, resulting in N—S trending rifting. It is even possible that parallel stresses have acted as far to the east as Franken (Frankische Furche). Most active volcanism typifies the rift in Hessen and the Rhön. The Vogelsberg is by far the largest volcano of Central Europe, covering 2500 square kilometres with basaltic effusives; very numerous smaller eruptive vents dot the country as far north as Kassel and the Reinhardswald.

Although the Vogelsberg marks the extension of the Rhine rift through Hessen and Hannover in the general direction of Oslo, certain other remarkable features point to the northwest in the direction of Cologne and the Kölnische Bucht. N—S faults are little in evidence here, but a zone of very active volcanism, with largely basaltic effusives, indicates certain deep seated connections between the Basin of Mainz and the Kölnische Bucht. They begin as small necks in the region of Rüdesheim and Wiesbaden, become quite conspicuous in the Westerwald and the Eifel, and continue as far as Bonn (Siebengebirge) and Siegburg. These activities date all the way from Miocene to late-Pleistocene (Laacher See explosion). The basalts are Miocene.

Another old-Mesozoic line of weakness leads from Luxembourg in N—S direction towards the Kölnische Bucht. It is this connection that is marked by the volcanism of the Eifel. The leading direction of the faulting is here SW—NE, characteristic for the entire eastern rim of the Basin of Paris and the Hunsrück-Taunus ridge. Oligocene rifting contouring the Ardennes mass and the Brabant Massif may, however, play a part in the deep subsurface. Conditions which we can observe at the surface are far from conclusive. Anyhow the great central fault-trough of the Netherlands (Groote Slenk), notably from Roermond on, has all the earmarks of the other rifts, although the general direction swings off to the NNW and NW, possibly connected with the contouring of the Brabant mass. Movement was certainly very active in Oligocene time, when the Rhone-Rhine rift had its maximum activity. An enormous thickness of marine upper-Oligocene was proven in borings near Vlodrop, east of Roermond, and also on the western side near Maeseyck. Farther to the north we only know, similarly as in the Kölnische Bucht, that periodic downfaulting continued all through the later Tertiary and the Pleistocene; here the Oligocene was no longer reached in borings. It would, therefor, seem possible that this trough was a more western fracture of the same general nature as the rifts in the Plateau Central. A median line of horsts is indicated along the full length of the Köln-Netherlands trough, beginning in the Ville, continuing in the Vierssen horst and the Peel horst. A farther extension of this median line of uplifts can be traced over Mill (near Boxmeer) in the direction of Amsterdam (het Gooi). Pleistocene movements on NW faults are conspicuous all over the Kölnische Bucht and South Limburg; they increase enormously in importance towards the northwest. In the already mentioned borings near Vlodrop the following relative displacements were noted as between the Peel-horst and the graben :

at the top of the upper-Oligocene :	515 m;
within the Pliocene :	288 m;
at the base of the Pleistocene :	226 m.

The main depression runs in the direction of Alkmaar, with the median high still clearly in evidence. (**13**)

Between Scotland and Ireland there exist indications of another similar rift, *the Minch Channel,* which has decided points of similarity with the great more eastern rift of Continental Europe. It has the same typical features: upturning of adjoining blocks, fissuring independently across older transverse massifs, and Tertiary volcanism. Most of the rift is presumably submerged under the Irish Sea and the Atlantic. Shears suggest a relative displacement of Ireland towards the south. Volcanism is very much in evidence. The Paleozoic and older platform is depressed below sealevel within the fault-trough; present high ground, including the Plateau of Antrim, consists mainly of Tertiary basalt, the flows of which reach aggregate thicknesses of between 500 and 1000 metres. Relicts of Mesozoic beds (upper-Cretaceous) exist in Antrim. The flows of lava cannot be dated accurately, but it is suggested by plant remains that part of the tuffs may be of Eocene age, consequently this more western rift may have had an earlier origin than the Continental Oligocene ones. Similar volcanics as in Antrim, occur in Arran, on Mull and Skye, in Scotland, and other smaller islands within the Minch. On Mull, Skye and Eigg the basalts are also associated with Eocene leaf-beds, indicating that this area was let down between the Outer Hebrides and the mainland of Scotland. It is possible that the later phases of igneous activity were prolonged into subsequent divisions of Tertiary time.

Farther south in the Irish Sea no similar volcanism is known, the only point being the Wolf Rock, 30 km SW of the Land's End (phonolite). One has to go far out into the Atlantic west of Ireland to find similar effusives: Rockall, 380 km west of the Outer Hebrides, and the shoals of the Porcupine Bank, 275 km west of Ireland.

A great deal of controversy has existed whether these great rents in the continental mass of Europe are *rifts or ramps*, in other words whether these fault-throughs, with their upturned sideblocks, are due to subsidence — whether it be gravitational along the apex of an old arch, or through tension —, or whether (ramps) they are the result of compression, the downthrust center between two upthrust jaws, connoting, at least in part, a high angle attitude. The writer favors the true rift explanation. He argues that a structural feature of such enormous lateral dimensions (1800 km in length from the Rhone mouths to either Mjösen or the North Sea) cannot be explained in any other way than by westward stretching and fissuring of the continental block of Europe, similarly as we whitness in Africa. There also it is not a clean-cut single fracture, but a zone of fissures and fault-troughs of varying direction in details. The primary cause would have to be continental west-drift and the tearing open of the Atlantic. The relative smallness of the westward stretching as compared to the enormous compression caused by the northward drift of Gondwana, active through the entire upper-Paleozoic, and again through all later-Mesozoic—Tertiary times, should not close our eyes as to the primary importance of rifts of such length, associated with so much deep seated volcanism. Much of the argument has centred around more closely studied local features, like the Upper-Rhine Graben and Hessen. The problem cannot be put so simply, interesting though these studies are. Naturally these immense crustal fractures are very complicated, and what we observe is only the very superficial effect of a deep rent in the lower crust. They all originated in the Tertiary, but — although they are conspicuously autonomous — in certain areas they apparently follow lines of weakness. This would have to be expected, and is also the case in Africa. If westdrift, and resultant westward stretching are the primary cause, many other stresses and resistences in the complicated mosaic of the outer crust are certain to confuse the picture. Simultaneously there has occurred relative

N and NE drift of notable regions in the platform, setting up shearing and, quite probably, local reversal of stretching into temporary compressive forces. Then we have quite considerable, probably largely isostatic changes of level of several great crustal units to confuse us. In certain areas these movements affect parts of the rift-trough itself, and are apt to have effaced its surface character over a considerable expanse. Then the local reaction of the superficial crust to the rifting, which took place in the deep crystalline crust at some scores of kilometres below the surface, is naturally variable. In some places the fault-trough effect is very much more pronounced than elsewhere, in other places it is mainly volcanic activity (deep basic subcrustal magmas!) that indicates the deep rent in the crust, whilst the surface remains more or less undisturbed, or merely shows some sagging. The filling of the resultant void can take place either by sediments from above, or by magma from below. The masses of lava that poured out at the surface are sometimes enormous. It is impossible, therefor, to decide so simply, from a few local observations, whether the great Rhone-Mjösen fissure, with its many side branches, taken as a whole, is a rift or a ramp. A fracture of such dimensions is evidently caused by major crustal movements of a far greater order of magnitude than any of its local and superficial effects. These latter are only incidents, variable as to local conditions, and to be viewed and interpreted as such.

CONCLUSIVE SUMMARY.

The Variscan folding and intense overthrusting had caused great zonal duplication of relatively lighter crustal rocks and these areas have remained active isostatically. After general consolidation had progressed, following the Permo-Carboniferous revolution, the folded area had become a firm corrugated crust of great resistence, particularly to forces operating at an angle to the original strike. The rigidity, however, became locally weakened. This was particularly the case where the substructure became depressed under deep Kimmeric and older basins with more recent filling. The location of such basins may have been caused either by a preexisting local weakness in the crust, by isostasy, or by deepseated pressures from the initial stages of the Alpine orogeny. In the Mesozoic the northward creep was revived, but a greatly changed crust became subject to it on the Alpine foreland. Yielding became very differentiated and locally variable, in accordance with local substructural differences in rigidity. It is natural to expect the non-homogeneous crust to give way along shear lines, directed in the general direction of the creep, but now on a much larger scale than before it became solidified to its present extent. True folding would not anymore take place easily, but crustal shortening must principally have happened along strike faults, blockfolding, or broad basement-warping (undation). Folding would be confined to areas of enhanced lability in the deeper basins. Roughly N—S lines of weakness were caused, which at first expressed themselves only as sagging. When finally the west of Europe became subject to Tertiary stretching in conjunction with the opening of the Atlantic, a few great rifts formed: first the Minch-Irish Sea Rift in the west, and shortly after the Rhone-Rhine-Mjösen Rift a little farther east, with a presumable great side branch traversing the Netherlands and the northern North Sea. The movements of the great crustal units between these major fractures became differentiated. There appears a natural tendency of the more western blocks to lag behind in the general creep towards the north, resulting in an apparent southward sliding of the western units relative to their eastern neighbors, and shear structure. Some blocks may have become rotated. The importance of the few major rifts as crustal fractures of a higher order is indicated by prolific outpouring of deep subcrustal magma at many points along their course (alternating of course with more acid products of later differentiation or melts caused by fusion). These effusives are most conspicuous on the geologic map where older crustal blocks were split open and the basement platform outcrops at the surface.

Broad zones of shearing were set up at many localities. Local variations in rigidity of older, probably deeply rooted masses like the Brabant Massif, or more solidified substructural units like the Rheinische Masse, the Ardennes and the Harz Mountains, cause interruption of the regularity of the picture, anomalies in the general trends and in the yielding to deformation. Northward drift is clearest expressed in the Rheinische Masse and the Harz, complicated by salt tectonics. Another set of structures runs through it all, a widespread fracturing of Continental Europe along a prevalent WNW—ESE direction, parallel to the southwestern edge of the Russian Table. Possibly these also may be an effect of compression on a broad scale, warping and fracturing of the basement, under the influence of northward pressures from the two great orogenies, but deflected by a lateral resistence from the massive Russian Plateau. All this caused an extremely complicated mosaic of blocks, which by their relative displacements set up a multitude of local stresses and resultant minor deformation, obscuring *the primary pattern.*

This latter remains, *first* and principally: *regional crustal creep towards the north* into the triangular space between Eria and Fennoscandia, between the Russian Table in the east and the thoroughly consolidated Caledonide blocks in the west, with some minor rigid nuclei between: the Brabant Massif, the Ardennes and Rheinische Masse block, Moldanubia, the Plateau Central and Armorica. (Others may be hidden under the later filling of the deep basins). In this reentrant the successive Variscan and Alpine arcs had pushed themselves with increasing convexity towards the north. *Secondly:* autonomous N—S *rifting* of the entire West-European crust by continental west-drift, in conjunction with the opening of the Atlantic.

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LITERATURE.

1. R. BÄRTLING, Tiefbohrkarte des Niederrheinisch-Westfälischen Steinkohlen-Beckens (Blatt Münster i/W) 1 : 100.000. Preuss. Geolog. Landesanst., Berlin (1927).
2. H. BREDDIN, Die Bruchfaltentektonik des Kreidegebirges im nordwestlichen Teil des Rheinisch-Westfälischen Steinkohlenbeckens. Glückauf, Nos. 34—35 (1929).
3. S. VON BUBNOFF, Erdgeschichte und Bewegungsbild der Erde. Zeitschr. für die gesammte Naturwissenschaft, 185—204 (1936).
4. S. VON BUBNOFF, Geologie von Europa, in Geologie der Erde, herausgegeben von E. Krenkel. Berlin (Bornträger) (1926) (1930) (1935—'36).
5. A. GROSJEAN, Indices de sollicitation tectonique horizontale dans le bassin houiller de la Campine belge. Bull. Soc. Belge d. Géologie, T. XLV, 120 (1935).
6. B. GUTENBERG and C. F. RICHTER, Depth and geophysical distribution of deep-focus earthquakes. Bull. Geol. Soc. Amer., Vol. **49**, 249—288 (1938).
7. W. VON SEIDLITZ, Grundzüge der Geologie von Deutschland. Jena (Fischer) (1933).
8. G. L. SMIT SIBINGA, On the relation between deep-focus earthquakes, gravity and morphology in the Netherlands East Indies. Gerland's Beiträge zur Geophysik, Vol. **51**, 402—409 (1937).
9. H. STILLE, Die Osning Ueberschiebung. Abh. d. Preuss. Geolog. Landesanstalt, No. 95 (1924).
10. H. STILLE, Zur Palaeogeographie des nordöstlichen Niedersachsens. Nachr. v. d. Gesellsch. d. Wissenschaften zu Göttingen (1932).
11. F. ED. SUESS, Bausteine zu einem System der Tektogenese. Berlin (Bornträger) (1937).
12. W. A. J. M. VAN WATERSCHOOT VAN DER GRACHT, The Permo-Carboniferous orogeny in the South-Central United States. Proc. Royal Netherlands Acad. Amsterdam, Vol. XXVII, No. 3 (1931).
13. W. A. J. M. VAN WATERSCHOOT VAN DER GRACHT, A structural outline of the Variscan front and its foreland from South-Central England to eastern Westphalia and Hessen. Compte Rendu 2nd Heerlen Congress on Carboniferous Stratigraphy, 1485—1565 (1935, published 1938), with a tectonic map from the English Midlands to Hessen.