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Possible significance of Eurafrican wrench-fault zones: differential drift and driving mechanism

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Summary

NW-SE oriented wrench-fault zones, crossing part of France, Switzerland and part of Italy, are described from field observations and reflection-seismic data. Their present-day structural surroundings imply a paleogeographic framework, that led to define them as late miocene to recent deformations, located along hercynian transcurrent Arches, on either side of the old Rawil-Doubs Graben.

This Rawil-Doubs Graben is taken to be a segment of a large tectonic feature, which can be traced from North Africa to the North Sea and farther into the Norwegian offshore.

It turns out that such a transcontinental structure displays an arcuate shape, with a westerly directed convexity, and is roughly parallel to the northern portion of the Mid-Atlantic ridges and rift-valleys. Structures of similar configuration are found in Eastern Europe too.

From a geological and geophysical viewpoint, the present authors consider such a parallelism of arc-shaped disolocation-lines as expressing what is herein called a «differential drift» and they find the conventional sea-floor spreading hypothesis inadequate to explain it. In a long search for a substitute, they were, finally, faced with that sort of chicken-and-egg-problem:
IS THE SEA-FLOOR SPREADING THE CAUSE OF THE CONTINENTAL DRIFT OR, INVERSELY, DOES THE SEA-FLOOR SPREADING RESULT FROM THE DISPLACEMENT OF THE CONTINENTS?

On the basis of the differential drift concept and after repeated analytical, numerical and experimental processes had been used, a driving mechanism is proposed, i.e. a force able to produce the continental drift and the ensuing openings and spreading of the sea-floor.

Zusammenfassung

NW-SO verlaufende Störungszonen, die einen Teil Frankreichs, die Schweiz und einen Teil von Italien durchqueren, werden auf Grund von Feldbeobachtungen und von reflexionsseismischen Daten beschrieben. Die Strukturen, die sie gegenwärtig umgeben, deuten einen paläogeographischen Bau an, der dazu führt sie als spätmiozäne bis rezente Verformungen zu deuten, die entlang hercynischer durchlaufender Hochzonen zu beiden Seiten des alten Rawil-Doubs Grabens zu liegen kommen.

Dieser Rawil-Doubs Graben wird als ein Segment einer grossen tektonische Einheit angesehen, die von Nordafrika zur Nordsee und weiter in das Offshore Gebiet Norwegens verfolgt werden kann.

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Es zeigt sich, dass eine solche transkontinentale Struktur einen bogenförmigen Verlauf hat, mit einer nach Westen gerichteten Konvexität und dass sie annähernd parallel mit dem nördlichen Abschnitt des Mittelatlantischen Rückens verläuft. Strukturen von ähnlicher Ausbildung findet man auch in Osteuropa.

Aus geologischer und geophysikalischer Sicht, betrachten die Autoren dieser Arbeit eine solche Parallelentwicklung von Verformungen als Ausdruck von etwas was sie hier als «Differential Drift» bezeichnen und sie denken, dass die übliche Hypothese des «sea-floor Spreading» zur ihrer Erklärung nicht reicht. Bei der Suche nach einer alternativen Erklärung sahen sie sicht mit jener Art von Huhn-und-Ei Problem konfrontiert:

IST DAS «SEA-FLOOR SPREADING» DIE URSACHE DER KONTINENTALVERSCHIEBUNG ODER, UMGEKEHRT, IST DAS «SEA-FLOOR SPREADING» EINE FOLGE DER VERSCHIEBUNG DER KONTINENTE?

Auf Grund des «Differential Drift» Konzepts und nach der oftmaligen Anwendung analytischer, numerischer und experimenteller Verfahren, wird ein Kräftemechanismus vorgeschlagen, d.h. eine Energie, die imstande ist die Verschiebung der Kontinente und die sich daraus ergebenden Zerreissungen am Ozeanboden und auf dem Festland zu erklären.

Résumé

A partir d'études sur le terrain et des résultats de campagnes sismiques, une description est donnée des zones de décrochements qui du NO au SE, traversent une partie de la France, la Suisse et une partie de l'Italie. Le cadre paléogéographique qu'impliquent position et configuration des structures actuelles amène à considérer ces décrochements comme des déformations, d'âge miocène supérieur à récent, situées le long de dorsales transverses hercyniennes et de part et d'autre de l'ancien fossé du Doubs-Rawil.

Ce fossé du Doubs-Rawil semble bien n'être qu'une partie d'un important accident tectonique, dont les traces peuvent être suivies des rives méridionales de la Méditerranée à la Mer du Nord et au-delà, au large des côtes de la Norvège.

Prise globalement, cette déformation transcontinentale revêt la forme d'un arc à convexité tournée vers l'Ouest et apparait plus ou moins parallèle au segment nord de la dorsale médio-atlantique. De semblables déformations parallèles existent également en Europe orientale.

Géologiquement et géophysiquement parlant, un pareil parallélisme exprime un phénomène que l'on appellera, ici, la «dérive différentielle», phénomène dont ne saurait rendre compte l'hypothèse de l'expansion des fonds océaniques. Dès lors, d'autres voies s'ouvrant à la recherche, on s'est trouvé confronté au problème d'établir SI L'EXPANSION DES FONDS OCÉANIQUES, PLUTÔT QUE D'ÊTRE LA CAUSE DE LA DÉRIVE CONTINENTALE, N'EN ÉTAIT PAS LA CONSÉQUENCE?

Fondé sur le concept de la dérive différentielle et sur les données obtenues par l'analyse mathématique et l'expérimentation par modèle analogique, un mécanisme de la dérive continentale est proposé, un mécanisme procédant d'une énergie apte à déplacer les masses continentales et à provoquer, par ce déplacement même, l'ouverture des fonds océaniques.

Contents

List of figures and plates

Introduction

On the basis of a regional study carried out in Western Switzerland, and from the analysis of 310 kilometres of seismic lines surveyed in 1974, in the same area, the Thunersee-Charquemont wrench-fault was defined, in 1978, as a SE-NW trending tectonic feature, crossing the Molasse basin and parts of the adjacent Jura and Prealps mountain ranges (CHENEVART 1978).

Since then, i.e. in 1981, there have been 120 kilometres more of seismic lines surveyed by BP (British Petroleum International Limited) through the Thunersee-Charquemont wrench-fault (actually a wrench-fault zone) and SW of it.

The convergence of the most oustanding facts, brought out by both the 1974 and the 1981 surveys, stressed the need for the regional study to be resumed from the point where it had been left off in 1978. Thus, started in spring 1982, the present work first covered the area comprised between the lake of Thun, the Préalps, the lake of Geneva, Pontarlier and Biel (Fig. 1) and was then extended, south-eastwards, to the Alps up to a line joining Aosta to Domodossola, on Italian territory, and, north-westwards, across the Folded Jura up to the Besançon area, on French territory.

The study mainly consisted of detailed mapping of surface structures with an attempt to establish, within the limits of the Swiss Molasse basin, subsurface structure contour maps (Cretaceous and Dogger markers) by integrating, to the seismics, the data provided by the deep oil wells drilled in the area, from 1940 to 1982. Figure 1 shows the location of these wells.

Special attention was directed to the surface structures transected by the Pontissalian wrench-fault zone (décrochement de Pontarlier). For reasons that will be discussed more fully later on, this zone, well konwn in Pontarlier area (the type-locality), is herein taken to cut through the Jura, mainly in a SE-NW direction and, hence, to be parallel to the Thunersee-Charquemont wrench-fault zone.

As illustrated in Plate I, we postulate that both wrench-fault zones extend to the SE and to the NW and, bounding, as they do, the Pennic, the Prealpine and the Bisontine Arcs, they seem to control the present shape of the Arcs. If such were the case, this would strongly suggest a process whereby some positive structures which, in a previous system, occupied the site of the zones, have influenced the morphogenesis of the Arcs.

The facts, from which our postulates ought to acquire support, will be briefly described in chapters 1 to 4. We shall, then proceed from those observable facts to their implications, from specifics to generalizations, namely in part of chapter 4 to chapter 7.

Drawn from these facts and reasoning and from further data given in chapter 8, our general conclusions may appear, if not purely speculative, at least as being coupled with a hint of subjectivity, what we concede. Nevertheless, when dealing with our postulated transcontinental strike-slip faults, we confront fundamental problems that cannot be dodget and that plead for a reappraisal, in depth, of some concepts held by the sea-floor spreading hypothesis.

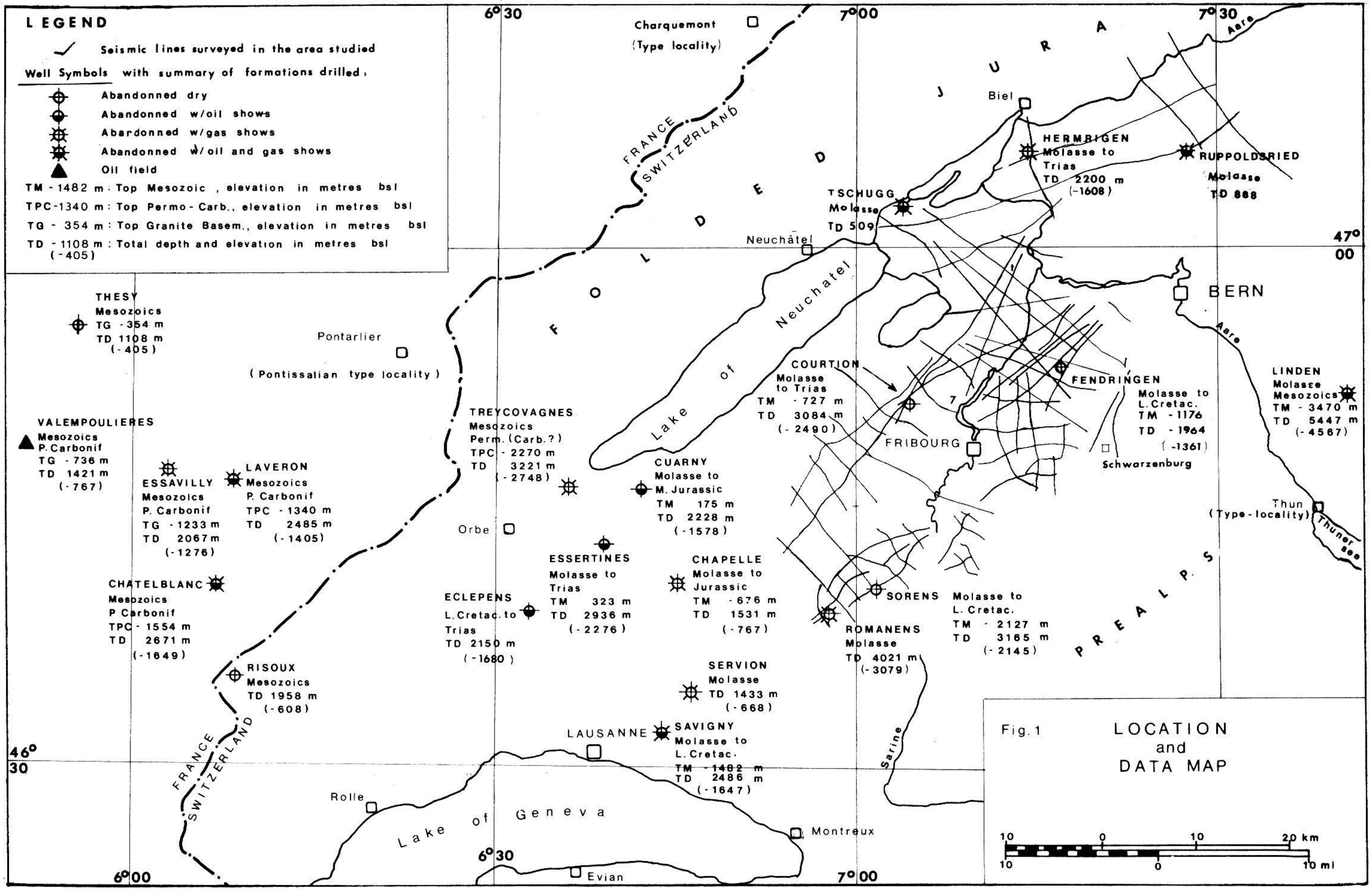

Fig. 1 LOCATION and DATA MAP

1. The Thunersee-Charquemont and the Pontissalian wrench-fault zones in their type-localities

1.1. *The Thunersee-Charquemont wrench-fault zone,* as defined in 1978, is best observable along the north-western end of the lake of Thun (Thunersee) and in its surroundings, on the one hand, and, on the other hand, in that part of the Swiss and French Jura located SE and NW of the village of Charquemont (Fig. 1).

Although, along the Thunersee, the wrench-fault are left unmapped on the Tectonic Map of Switzerland, on 1:500.000 scale, their effects are clearly shown on this map. The most conspicuous of these effects is the dextral displacement of the subalpine Molasse. Furthermore, the eastern border of the Prealpine nappes is, there, strongly disturbed (CHENEVART 1978, page 57).

From the Thunersee area north-westward, shearing movements affect tertiary surface structures up to the vicinity of Schwarzenburg. There, erratic dips appear on the eastern flank of the S-N trending Wünnewil anticline. The previously mapped, short, squat, W-E striking Schwarzenburg anticline (FRASSON 1947) is likely to result from a distortion effect along the dextral strike-slip zone.

From Schwarzenburg we enter the area covered with a dense network of seismic lines (Fig. 1) and in which the wrench-fault zone has been identified with aseismic sections (blind areas) well delineated on the seismograms and aligned in a SE-NW direction (OP. CIT. 1978). The linear distribution of these reflection anomalies constitutes a kind of «structure devide»; actually, subsurface and surface anticlines and synclines, situated south of the «divide», are well-developed S-N trending structures, while their homologous, located north of the «divide», are small, flat-topped, SW-NE trending structures (Pl. I).

Such an abrupt shift of structure axis, that had not been clearly recognized in the alluvial plain comprised between the lakes of Murten, Neuchâtel and Biel, in the course of the seismic campaign of 1974, appears clearlier on the structure contour maps we traced on the basis of the relatively few but crucial data collected from the 1981 vibroseismic survey. However, fairly evident as it may have been, the existence of the SE-NW running wrench-fault zone, in said alluvial plain, needed more factual support. This support was amply supplied by the gravimetric surveys carried out by the geophysic institutes of the universities of Geneva, Lausanne and Zurich, under the supervision of Professor C. Meyer de Stadelhofen. Among the maps produced, let's mention the most meaningful ones in terms of structural geology, i.e.: Axelrod's maps of Bouguer anomalies, Residual analytics, Gravific axis, Basement isohypses (A. AXELROD 1978) and the New gravimetric map of Switzerland (E. KLINGELE and R. OLIVIER 1980, with the contribution of H.G. KAHLE).

From the alluvial plain, rise abruptly the Jura mountain ranges. The effects of wrench-faulting reappear on the surface, being peculiarly well observable in the triangle Lignières-Le Pâquier-Villeret, where spots such as Vergneux, Chenau, Le Fornel, Combe Grède, display those chaotic structural features that generally underline strong horizontal displacements of strucutres. The most important slip occurs between the Chaumont and the Chasseral anticlines (CHENEVART 1978). Noteworthy is the structure of the latter, becoming more and more complicated as it approaches the wrench-fault zone, a fact already expressed by Luthi in his geological profiles (E. LÜTHI 1954).

North of Combe Grèbe, the wrench-fault zone branches off in several directions, the main one remaining north-westward.

The wrench-fault zone can, then, be traced along the Doubs river and up to the hills surrounding the village of Charquemont and beyond, where its major expression is the sudden change of the anticlines and synclines trends (from SW-NE to W-E).

Thus, in its type-localities, the Thunersee-Charquemont wrench-fault zone constitutes a structural belt about 115 kilometres in total lenght and 4 to 7 kilometres in width.

1.2. *The Pontissalian wrench-fault zone* is located in the Franco-Swiss Jura. As understood in the present paper, its type-locality is the strongly faulted area bounded by a line joining the town of Orbe, the top of Mont Suchet, Pontarlier, Frasne, the top of Mont d'Or, the village of Berolle and following, then, the foot of the Jura up to Orbe. Thus, the Pontissalian wrench-fault zone includes the «décrochement de Pontarlier s.str.» described by various French and Swiss authors (AUBERT 1943, 1953, 1959, 1979, LAUBSCHER 1961, 1965, 1972) and characterized, on the Tectonic Map of Switzerland, by its predominantly N-S running strike-slip faults. This N-S orientation is substantially true between Berolle and the Mont d'Or and south of Pontarlier, but is far from being predominant in the concerned type-locality, taken as a whole. Besides the fact that some faults may be mapped in various ways, there are some good evidences that, even on the above mentioned map, the largest horizontal displacements of structure axis result from SE-NW trending wrench-faults. Seen from the top ofthe Mont Suchet, the low hills, sinistrally shifted from the Mont Tendre, are obviously intersected in that direction up to the vicinity of Pontarlier and Frasne. Thus, we deem justified to consider the Pontissalian wrench-fault zone, in its type-locality, as being roughly parallel to the SE-NW trending Thunersee-Charquemont zone.

2. South-eastern and north-western extension of the Thunersee-Charquemont and the Pontissalian wrench-fault zones

2.1. *South-east of its type-locality,* the Thunersee-Charquemont wrench-fault zone stretches in a direction parallel to the lake of Thun up to Leissigen, on the left shore, and Merligen, on the right one (Pl. I).

That segment of the lake of Thun exhibits, on both shores, strong effects of wrench-faulting on the surface structures (dextral strike-slip faults) as well as it discloses obvious seismic and gravimetric anomalies (Pl. I : shape of isanomalic lines 120 to 130). Noteworthy is the position of Laubscher's «Merligen triple junction» (H.P. LAUBSCHER 1982) near the point where the isanomalic line 130 swings abruptly to the south-east.

When crossing the lake, from Merligen to Leissigen, the Thunersee-Charquemont wrench-fault zone is about 6 kilometres in width, which means that it embraces the hilly area extendind form the Thunersee to Reichenbach in the Kander valley. In the lowest parts of the three main valleys, which debouch into this area, our field investigations failed to give an accurate account of wrench-faulting, because these parts, with the exception of some scattered outcrops, are filled with fluviatil deposits and moraines.

From the quaternary-covered area, we went upwards into the three valleys, Kandertal, Kiental and Suldtal. While, in the Kandertal-Lötschenpass area, we recognized the structural features which Laubscher has termed «complementary shears» (H.P. LAUBSCHER 1982, page 234), we are disinclined to take them to be the southern continuation of the Thunersee wrench-fault zone. In fact, the somewhat chaotic mountain ranges, comprised between the Kiental and the Suldtal, offer much more structural characteristics relevant to wrench-faulting than does the Kandertal-Lötschenpass area.

Hence, it may fairly be said that the Thunersee-Charquemont wrenche-fault zone is very likely to extend, in a SE direction, through the Faulenmatt-Obere Suld Alpen, located between the SE-NW stretching valleys (Kiental and Suldtal) and, from there, across the intensively faulted Dreispitz-Schwalmern Massif of the Wildhorn nappe.

As shown in Plate I, the Thunersee-Charquemont wrench-fault zone runs farther south-eastward, its effects being well observable in the strike-slip displacements affecting the autochthonous Mesozoics, south of the Schilthorn.

There are increasing difficulties to follow the wrench-fault zone through the crystalline Aar massif and down to the Rhone valley and the lower Vispertal. Such as we have mapped it, this zone passes between the Bietschhorn nad the Aletschhorn (Pl. I), runs, then, parallel to the SE-NW trendind Stockhorn ridge and crosses the Rhone valley between Visp and Naters. The mapping of this segment consists essentially of interpolations between distant points, where strong tectonic disturbances appear, and, hence, may lack of strict objectivity. The same remark applies to our mapping between the Rhone valley and the Vispertal-Salinatal-Simplon area. From this area, south-eastward, our field work was just a routine check of the widely known Simplon fault, which we consider as being, from the Simplonpass down to Domodossola, the best observable SE extension of the Thunersee-Charquemont wrench-fault zone.

2.2. *North-west of its type-locality,* the Thunersee-Charquemont wrench-fault zone, shifting the axis of homologous structures, can be followed along a line joining Charquemont-East, Maîche, St. Hippolyte on the Doubs bend, and the eastern end of the Lomont Mountains, in the French Folded Jura. For a distance of about 20 kilometres, the Lomont Mountains consist of a remarkably continuous, W-E oriented range of hills, abruptly interrupted and distorted by strike-slip faults, well observable in the triangle Noirefontaine-Montécheroux-Pont de Roide and farther north-westward, across the Doubs river, up to the Chanet, Onans and Mervelise valleys (Pl. I).

2.3. *As regards the Pontissalian wrench-fault zone in its south-eastern extension,* a mere glance at the Tectonic Map of Switzerland, on 1:500.000 scale, renders fairly evident the fact that the SE-NW oriented faults system, delimiting the Mormont cretaceous limestone, is the continuation of the Pontissalian wrench-faults zone of the type locality, described in the foregoing chapter 1.2.

Farther south-eastward (Pl. I), the effects of wrench-faulting are to be found in the burdigalian Molasse of the Jorat, where the wrench-fault zone coincides with a narrow, elongated water-divide down to the area adjacent to the plain, where the Broye river makes a sharp turn, north of Tatroz.

This segment, comprised between the Mormont and the eastern end of the lake of Geneva, is roughly parallel to the gravimetric anomaly expressed by the isanomalic lines 60 to 90 (Pl. I) and includes a part of the Jorat magnetic anomaly, to follow, then, the SE-NW oriented flank of Mont Pèlerin.

From the lake of Geneva, southeastward, to Martigny, and from there to the Italo-Swiss border, our field investigations were greatly facilitated by the works of the numerous authors, who have dealt with this area or with the Swiss Alps in general. Two maps, on 1:25.000 scale, have particularly been used: the map 1305 Dent de Morcles (H. BADOUX, M. BURRI, J.H. GABUS, D. KRUMMENACHER, G. LOUP, P. SUBLET 1971) and the map 1325 Sembrancher (M. BURRI, L. JEMELIN, N. OULIANOFF, S. AYRTON, P. BLANC, K. GRASMUCK, D. KRUMMENACHER, J. RAUMER, P. STALDER, R. TRÜMPY, B. WUTZLER 1983).

There is little doubt as to whether the Rhone valley, from the lake of Geneva to Martigny, runs along a tectonic anomaly or is a mere erosional feature. Its tectonic nature and, hence, its identification with the south-eastern extension of our wrench-fault zone, is emphasized by the differences in structural attitude and altimetric data of the formation exposed on the left and on the right bank of the Rhone river. Let's mention a few ones of these differences:

— Abrupt shifting of the structure axis, from the Chablaisian (left bank) to the Romande Prealps (right bank), both prealpine lobes being affected, on their versant, by predominantly SE-NW oriented strike-slip faults.

— Change in the direction and gradient of the axial plunges of the Aiguilles Rouges/Mont Blanc crystalline massifs and horizontal displacement of their strikes, the Vallorcine granite, well exposed on the left bank, being strongly mylonitized in the vicinity of Mieville and being no longer to be found on the right bank of the Rhone river.

— Steeper dips and higher altitude on the right bank than on the left one, in the Morcles nappe and the parautochthonous Mesozoics.

Furthermore, a well defined gravimetric anomaly, all along the Rhone valley (E. KLINGELE and R. OLIVIER 1980), cuts through the various units of the Prealps (Pl. I: isanomalic lines 90 to 130), the Morcles nappe, the Aiguilles Rouges/Mont Blanc crystalline massifs and their adjacing parautochthonous, and streches, then, up to Martigny and beyond, to reach the western border of the Pennic nappes.

For clarity'sake we shall, now, add to the term Pontissalian, the epithet octodurian (from Octodurus meaning Martigny) and deal, henceforth, with the Pontissalian-Octodurian wrench-fault zone.

South of Martigny and, up-stream, on the left bank of the Rhone river, the Pontissalian-Octoduriam wrench-fault zone is about 6 kilometres wide. Its major effect is the present structural position of the N 50° E trending gneiss and schists complex of Mont Chemin, a shifted part of the submeridian Mont Blanc massif. Drastic strike incurvation of strongly mylonitized gneiss and schists is observable in the vicinity of Le Brocard-La Drance, while in Le Planard-Col des Planches area, these same gneiss and schists are affected by numerous sinistral displacements.

From Mont Chemin, south-eastward, large areas are covered with quaternary deposits. However, crystalline rocks are well exposed on the south-western flank of the Mont Catogne and in the easier accessible Durnand canyon. Detailed examination of these various outcrops convices that there can be no doubt about Oulianoff's statement that the Durnand d'Arpette valley results from a N 34°W oriented faults system (OULIANOFF 1973, page 10). We take this valley to be the south-western border of the Pontissalian-Octodurian wrench-fault zone, a zone that includes the whole of the strongly faulted block of the Mont Catogne, down to approximately the Entremont valley.

From the Mont Catogne, the Pontissalian-Octurian wrench-fault zone extends south-eastward, through the morphotectonic unit of Vella - La Tsavre, which is comprised between the two SE-NW oriented strike-slip faults of the middle Entremont and the upper Ferret valleys; it runs, then, across the St. Bernard pass, towards the St. Rhemy-Val de Menouve-Allain triangle, follows the lower SSE flowing Buthier stream and reaches the Dora Baltea river in the vicinity of the Italian town of Aosta (Pl. I).

2.4. *North-west of its type-locality,* in the Franco-Swiss Jura, the Pontissalian (-Octodurian) wrench-fault zone streches in a parallel direction with the line Pontarlier-Chaffois-Levier. Along that line, south of it, the zone is 8 to 12 kilometres wide and gives rise to a very noticeable change of geometry of anticlines and synclines, truncating them as in the Côte du Fol, shifting their axis as in the rolling hills of Scay-Maublin-Chapelle-Byans.

About 6 kilometres NW of Scay, the effects of the cross-cutting faults are peculiarly well observable in the structures surrounding the village of Lemuy, where sudden incurvations of La Joux longitudinal fault and sinistral displacements of jurassic blocks take place.

From Lemuy north-westward, the area of major disturbances, comprised between Dournon, Nans-sous-Ste Anne and Salins-les-Bains, is encompassed within the Pontissalian-Octurian wrench-fault zone (Pl. I), a zone that extends farther towards St Thiébaud and beyond, outside the area studied.

3. Main structural units exposed between the two wrench-fault zones and along their outer margins

The Pontissalian-Octodurian and the Thunersee-Charquemont wrench-fault zones, as descibed in the foregoing chapters, delimit an area about 195 kilometres in length and 50 to 75 kilometres in width (Pl. I). This area comprises parts of various tectonic entities, i.e., from SE to NW, the Italo-Swiss Pennine nappes, the Helvetic and Prealpine nappes, the Swiss Molasse basin and the Franco-Swiss Folded Jura.

With the exception of the Molasse basin, these tectonic entities are generally well exposed, but their most conspicuous structural features are, no doubt, to be found at the front of the Pennine and Prealpine nappes and the Folded Jura, front consisting of strikingly arcuate mountain belts (Pl. I) herein termed:

— The Pennic Arc,
— The Prealpine Arc and
— The Bisontin Arc, respectively.

Clearly individualized, topographically as well as structurally, all located in the area comprised between the two wrench-fault zones, the Arcs disclose other characteristics, common to the three, as will be seen in the next paragraph.

The most prominent structural units, located along the outer margin of the Pontissalian-Octodurian wrench-fault zone, are, from SE to NW (Pl. I):

— The crystalline Massifs of Mont Blanc, Arpille and Aiguilles Rouges,
— The Dents du Midi (an axial culmination in the Helvetic nappes),
— The Chablaisian lobe of the Prealps,
— The Mormont (a high of lower cretaceous limestone, emerging from beneath the Tertiary of the Molasse basin),
— The Mont Tendre (an axial culmination and the highest summit of the Swiss Jura),
— The crystalline Serre Massif.

As regards the Thunersee-Charquemont wrench-fault zone, the major structures, exposed along its outer margin, are from SE to NW as follows (Pl. I):

— The axial culminations of the Simplo-Ticinese nappes,
— The crystalline Gotthard and Aar Massifs,
— The Faulhorn axial culmination in the Helvetic nappes,
— The Chasseral (an axial culmination and the third highest summit of the Swiss Jura, the second one being the Dôle),
— The crystalline Vosges Massif.

Due to its exiguity, Plate I does not show all the structures listed in the present chapter but, with the exception of the Serre Massif, they all appear on the Tectonic Map of Switzerland, on 1:500.000 scale.

4. The present-day configuration and surroundings of the Arcs and their implications in paleogeography

Thus far, the mere enumeration, in the foregoing chapters, of directly observable facts allows to outline the present-day configuration and surroundings of the area studied: an elongated, faults-bounded area crossing the Alps, the Molasse Basin, the Jura, and dominated, on either side, by structural highs situated outside the most external of the boundary-faults.

Let us now turn our attention towards the three arcuate mountain belts exposed within this faults-bounded area, namely the Pennic, the Prealpine and the Bisontin Arcs (Pl. I).

4.1. *The Pennic Arc* constitutes the front of the Pennine nappes. In the numerous theories put forward, from Argand (ARGAND 1916, 1920) to Trümpy (TRÜMPY 1955, 1960, 1973, 1980, 1983), there are marked differences of opinion regarding the Pennine nappes. Even though we do not fail to heed some of these theories, we still consider that process and timing of the emplacement of the Pennine nappes remain a matter of conjecture.

Perhaps less conjectural, however, is a fact implied in the preent-day configuration and surroundings of the Pennine nappes, taken as a whole, with axial plunges converging onto its middle part (Pl. I): they are lying in a graben-like structure, which might well represent the south-eastern extension of the Rawil depression, a transverse structural low located between the Mont Blan and the Aar structural highs.

About these Mont Blanc and Aar structural highs, let us postulate, as a premise to further inductive reasonings, that they are essentially hercynian crystalline massifs, successively rejuvenated by the kimmerian and the alpine orogenies, a premise often formulated, in the past, but that more recent concepts contradict. (Hercynian age has been confirmed by radiometric dating. ANDERSON 1978, page 163).

The present-day Pennic Arc, with its north-westwards directed convexity, shows a major horizontal displacement in its middle part, between Sion and Turtmann. These facts imply that the main driving force of the Pennine nappes tectonics was acting from SE to NW, pushing the nappes into the above mentioned pre-existing depression, that we shall, herein, term «the Rawil Graben».

From Sion and Turtmann, the present-day front-line of the Pennine nappes gradually swings to the SSW and to the SSE, respectively (Pl. I). From these facts it is inferred that the hercynian highs bordering, on either side, the Rawil Graben, i.e. the Mont Blanc, the Aar massifs and the south-eastern extension of the latter (underlying the culminating Simplo-Ticinese nappes) have passively taken part in the process of nappes emplacement, that is to say, that they have stemmed the nappes in motion, slowed down their borders more forcibly than their central part and, finally, stopped them in their north-westward advance.

So, conceived in a perhaps too simplistic way, our opinion is that the present-day Pennic Arc implies a paleogeographic framework that mainly consists of a SE - NW trending graben and lateral obstacle-massifs.

4.2. Jumping from the Pennic Arc to the north-westernmost part of the study area, we find, in *the Bisontin Arc* (Pl. I), the characteristics already mentioned in chapter 3: this Arc is topographically and structurally well individualized and is located between the Pontissalian-Octodurian and the Thunersee-Charquemont wrench-fault zones, as is the Pennic Arc.

To these characteristics we may add that the Bisontin Arc displays, at this particular northwestern boundary of the Folded Jura, a geometry and a position reminiscent of the Pennic Arc. Actually, both of them are north-west facing Arcs constituting the front of a tectonic unit, that is or was bordered by hercynian highs. For the Bisontin Arc, the latter are the crystalline Vosges Massif, to the north and north-east, and the south-eastern extension of the crystalline Serre Massif, to the south and south-east of the Arc.

Whereas surface field work provides sufficient convicing evidences for allowing to ascribe to the Vosges Massif the static rôle of lateral obstacle-massif, our knowledge of the south-eastern extension of the Serre Massif relies almost entirely on subsurface data. Actually, the results of the deep wells drilled along the outer margin of the Pontissalian wrench-fault zone (Pl. I and Fig. 1), combined with the rare seismic data at hand, disclose a continuous crystalline belt, which, from the Serre Massif (368 metres of elevation above sea-level), plunges south-eastwards to -354 metres in Thesy well, to an average of -690 metres in the seismically surveyed area, NE of the Valempoulières oil field, and to -1233 metres in Essavilly well.

Thus, we may reasonably consider as obvious the existence of the two lateral obstacle-massifs that the shape of the Bisontin Arc implies. But, what's about the graben that this Arc is, herein, taken to imply too?

As made plausible by altimetric data, collected in the Vosges and Serre crystalline Massifs, and by thickness measurements of the sedimentary sections comprised between them, we do not venture into the unknown by defining as a structural depression, the area delimited by the Bisontin Arc, the Thunersee-Charquemont and the Pontissalian-Octodurian wrench-fault zones. Owing to the tectonic style induced by its bordering faults and owing to the fact that it is almost entirely comprised in the French Doubs departement, we shall, henceforth, call this area the «Doubs Graben», a SE-NW trending graben which, as we may notice if we take a broader view, is remotely linked with that structural low located NW of Besançon and named the Morvano-Vosgien Straits.

As regards the possible south-eastern extension of the Doubs Graben, across the high mountain-ranges of the Swiss Jura, we cannot but recognize that the effects of the very complex Jura-building process have obliterated most of the pre-existing paleogeographic features, that the present-day Mont Tendre and Chasseral axial culminations (Ref. Chapter 3) might imply. We will, nevertheless, stress the axial plunges that occur from the Mont Tendre Jurassics towards the Tertiary of the Orbe-Grandson area, and from the Chasseral Jurassics down to the tertiary Molasse of Val de Ruz. These axial plunges, together with the large exposures of tertiary Molasse in the Cortaillod structural low and in numerous synclines, may be indicative of a global sinking of that portion of the Jura comprised between the Thunersee-Charquemont and the Pontissalian-Octodurian wrench-fault zones. The areal distribution of the gravimetric anomalies brings further support to the hypothesis of a graben transecting the Folded Jura (Pl. I: shape of isanomalic line 60; from the Gravimetric Map of Switzerland, on 1:500000 scale, by KLINGELE AND OLIVER 1979/1980).

4.3. The topographically and structurally well individualized *Prealpine Arc,* located between the Pontissalian-Octodurian and the Thunersee-Charquemont wrench-fault zones, constitutes the front of the Prealpine nappes (Pl. I). Field work brings out similarities between its geometry and that of the Pennic and the Bisontin Arcs. Actually, as these two arcs, the Prealpine arc displays a north-westwards directed convexity, which implies that the arc developped in response to an orogenic force acting from SE to NW, with the ensuing effect of a major horizontal displacement in the central part of the arc.

This almost rectilinear central part extends from the environs of Semsales to about the foot of the Gantrisch mountain range. From those two points, the front-line of the Prealpine Nappes swings south-southwestwards and south-eastwards respectively. Unlike the two other arcs, the Prealpine front-line is not dominated by surface highs, which might have played the part of lateral obstacle-massifs that would account for its incurvation; however, the Jorat magnetic anomaly (MEYER DE STADELHOFEN, SIGRIST, DONZE 1973) expresses a positive subsurface structure, which, presumably, occupies the site of an old high, to which such a rôle could be ascribed.

This magnetic anomaly, aligned in a SE-NW direction, with the present-day Mormont and Mont Tendre highs, culminates along the outer margin of the Pontissalian-Octodurian wrench-fault zone and is plunging towards the NE at an angle of 30 to 40°. The implication of such a plunge in that direction appears more clearly on the Gravimetric Map of Switzerland, which renders obvious the fact that, between the Prealpine Arc and the left bank of the Neuchatel lake, the area located NE of the Pontissalian-Octodurian wrench-fault zone is structurally lower than the one located SW of it (Ref. Pl. I: isanomalic lines 60 to 90).

This difference in elevation is corroborated by the petroleum exploration, carried out in that part of the Molasse basin facing the Prealpine Arc. In fact, along SW-NE section-lines, roughly perpendicular to the wrench-fault zone, we notice, in the deep wells drilled, the following differences in elevation, at the top of the mesozoic sequence (Fig. 1):

From:		To:		Diff. in elevation:	Distance betw. wells:
Savigny well,	-1482 m.	Sorens well,	-2127 m.	645 m.	27,5 Km
Eclepens well,	470 m.	Chapelle well,	-676 m.	1146 m.	16 Km
Eclepens well,	470 m.	Fendringen well,	-1176 m.	1646 m.	62,5 Km
Essertines well,	323 m.	Courtion well,	-727 m.	1050 m.	36 Km
Treycovagnes w.,	473 m.	Cuarny well,	175 m.	298 m.	7,5 Km

Even though these various data fail to define a tectonic style, such as an «horst-and-graben» style, they certainly allow to locate the border of a subsurface trough stretching along the north-eastern side of the Pontissalian-Octodurian wrench-fault zone.

What's about the opposite border and the central part of this presumed trough? Thanks to the seismic campaigns covering the area shown in figure 1, this question can be partly answered. Taking as a seismic marker the top of the mesozoic formation, we notice, south-west of the Thunersee-Charquemont wrench-fault zone, the broad Fribourg syncline (Pl. I) plunging southwards from -950 to -2200 metres, over a distance of 22 kilometres. Parallel to this syncline and east of it, the Wunnewil anticline plunges in the same direction.

North-east of the Tunersee-Charquemont wrench-fault zone, the axis of the Fribourg syncline and Wunnewil anticline are strongly shifted and their homologous, SW-NE trending structures, starting at an average altitude of -930 metres, reach their axial culmination, farther north-eastward, at about -800 metres.

As can be seen, the area located SW of the Thunersee-Charquemont wrench-fault zone is structurally lower than that located NE of it, at least in that part of the investigated area comprised between Schwarzenburg and the Neuchâtel lake, and further north-westward as confirmed by gravimetric surveys (Ref. Gravimetric Map of Switzerland, on 1:500000 scale). The question as to whether the differences in elevation result from abrupt vertical displacements or from gradual sinking and axial descent of the involved structures, cannot be answered for the time being.

Likewise, we are short of seismic data on the narrow belts bordering the wrench-fault zone, from Schwarzenburg to Thun. However, in the latitude of the latter and in front of the central part of the Prealpine Arc, the existence of a transverse, elongated sag is seismically demonstrated, the lowest point of the Fribourg syncline being at -2200 metres, as just quoted, whereas, to the NE and NW of that point, the Wunnewil and the Courtion anticlines reach an elevation of -1700 and -730 metres respectively, (elevations measured at the top of the mesozoic sequence). Furthermore, in one of the above-mentioned narrow belts bordering the Thunersee-Charquemont wrench-faults zone, a SE-NW oriented gravimetric anomaly could meet the requirements of our lateral obstacle-massif concept.

4.4. About *the Rawil Graben:* The space comprised between the Prealpine and the Pennic Arcs is occupied by the huge and complex mass of the Romande Prealpine nappes and a part of the Helvetic nappes. In spite of, or rather, because of their size and complexity, the Prealpine and Helvetic nappes have been the subject of a considerable concentration of work undertaken by several generations of geologists. A number of concepts, developped in earlier and recent times, are summarized in outstanding reviews of the Alpine geology, thus enhancing the main facts that allow to place structure-building events in their proper spatial relationship.

After having sought a balance between information gained in bibliographic studies and that from our own field observations, we consider as being widely admitted and fully justified the theory holding that the Prealps lie in a major tectonic depression (ANDERSON 1978, page 159), at least their Romande lobe. On the other hand, there are some fairly compelling evidences, which point out to the existence of a wide trough, beneath that portion of the Helvetic nappes comprised between the Pontissalian-Octodurian and the Thunersee-Charquemont wrench-fault zones. In fact, the SW-NE directed axial plunges, stemmed from the Dent du Midi culmination and from the Aiguilles Rouges, Arpille and Mont Blanc massifs, as well as the NE-SW directed axial plunges stemmed from the Faulhorn culmination and from the Aaar Massif, all are converging onto the Rawil Graben.

In brief, the implications, of the today configuration and surroundings of the Pennic, Prealpine and Bisontin Arcs have been defined as such, in the light of data provided by field geology, deep well drillings, seismic, gravimetric and magnetometric surveys. Even though certain facts remain indistinct, we think that there are fairly ample grounds for postulating that, in the period closely preceding the alpine orogeny, the implied paleogeography of the area studied mainly consisted of mountain-ranges aligned on either side of a SE-NW stretching depression, where they played a static part in the nappes emplacement process. A few remnants of these mountain-ranges, somewhat modified in their shape and trend, still subsist as today surface highs or, presumably, as unexposed structures underlying axial culminations. A large part of them, however, peculiarly between the Folded Jura and the Prealpine Arc, are at present hidden beneath the tertiary Molasse, hence their existence as ancient surface highs ought to acquire more convincing support than that obtained, hitherto, by mere implication. This will be seen in the pages to come.

As regards the present-day structural depression, the existence of which seems to be better established, we propose to term it the «Rawil-Doubs Graben».

5. Areal distribution of mesozoic sediments in Central Europe

— As outlined in chapter 4, in an attempt of palinspatic reconstruction, our postulated mountain-belts are 195 kilometres in length and extend on either side of the 50 to 75 kilometres wide Rawil-Doubs Graben. They strike at almost right angle to the general tectonic line of the today Western Swiss Alps and are taken to have constituted continuous mountain-ranges, from the Mont Blanc to the Serre and from the Aar to the Vosges crystalline Massifs.

Should such an important pre-tertiary orogen have existed beyond any doubt, be it as immersed or emerged highs, it would have controlled the areal distribution of a part of the mesozoic sediments deposited in its vicinity.

Now, what do we know about this areal distribution, within the autochthonous portion of the basins to which the study area pertains?

Numerous recent stratigraphic studies were concentrated on the Mesozoics exposed in the Folded Jura and, available as they are, they constitute a soundly based information. The same holds for the Mesozoics underlying the tertiary formation and disclosed by the deep wells drilled in the Swiss-Bavarian Molasse Basin. Some of the facts that have emerged from these various studies are the striking lateral variations in facies and thickness of well dated sediments comprised between the Triassic and the Cretaceous. With the aim of synthetizing these variations, several geologists have established isofacies, isopachs and other stratigraphic maps, most of which are meaningful, despite inevitable inter- and extrapolations. We shall briefly review some of the main mesozoic characteristics brought out by such maps.

— Triassic: On the paleogeographic map of the Muschelkalk, the authors (BÜCHI, LEMCKE, WIENER, ZIMDARS 1965) assume the isofacies lines to be slightly oblique and show the isopachs, in Western Switzerland, as being almost perpendicular to the general SW-NE trend of the present-day Alps. A nearly similar orientation is given to the Keuper formation. Noteworthy is the transverse position of the SSE-NNW oriented high that has, presumably, remained dry land during the Rhaetian.

Jurassic: Liassic isopic lines are running SSE-NNW in the study area, swing then north-eastwards with some embayments. The isopachous lines of the Lias are, in the area studied, broadly similar to those of the Triassic. The same observation applies to the Dogger isopachs. The above mentioned authors provide rare cartographic data on the Malm formation. Only one W-E oriented isopach is represented on the map of the Oxfordian (isopach 300 metres), all other curves being traced in dotted lines.

Cretaceous: Rapid lateral variations of facies and thickness of the Lower Cretaceous, in the Folded Jura and in the sequences underlying the Tertiary of the Swiss Molasse Basin, have been interpreted in various ways, but all converge to the fact that the Lower Cretaceous is confined to the area located south-west of a hinge line joining the Thunersee to the Bielersee and running farther north-westwards across the Folded Jura. This unchallenged fact is implicitly expressed by the above mentioned authors, in their map showing the areal distribution of the mesozoic sediments in Switzerland (OP.CIT. page 35). The broadly SE-NW oriented time lines characterize a pre-tertiary erosional surface and, hence, are not indicative of the location of the highs controlling the mesozoic sedimentation. Nevertheless, let us underline the fact that the limit of the extension of the Lower Cretaceous corresponds, broadly speaking, to the outer margin of the Thunersee-Charquemont wrench-fault zone.

Tertiary: At first sight, it would seem rather unlikely that our postulated SE-NW striking mountain-belts have controlled any part of the tertiary sedimentation in the area studied. However, we have to notice that D. Aubert has reported the Chattian formation as displaying evident facies variations from the southern flank of the Mormont high to the northern one (AUBERT 1959, pages 115, 116).

To sum up the matter, we may apply to the foregoing general picture, Trümpy's remark that paleogeographical units are rather ephemeral and subject to repeated shifting (TRÜMPY 1960). Still the fact remains, nevertheless, that the areal distribution of the autochthonous Mesozoics of Switzerland was controlled by structures, the trends of which were always, although at various angles, oblique to the general tectonic line of the present-day Swiss Alps. Before answering the question as to whether, among these various trends, the SE-NW trend may have been prevailing in its stratigraphy-controlling effects, we shall go for a stroll to see cursorily which additional data might be furnished by the Bavarian subsurface of the Molasse Basin.

— If only a very limited number of deep wells have been drilled in the Swiss Molasse Basin, this is far from being the case in its Bavarian north-eastern extension. On the basis of an intensively carried out petroleum exploration, K. Lemcke has collected a huge amount of surface and subsurface data from which spawned facts never faced previously. In the present study, we shall merely refer to his summary of the stratigraphic events, that took place from the Triassic to the Tertiary (LEMCKE 1970) and to his descriptions of tectonic movements that affected the Molasse Basin from the Permian to the Quaternary (LEMCKE 1974, 1977, 1981).

We have tried to draw together the facts on which Lemcke places special emphasis, namely the marine regressions, transgressions and the ensuing stratigraphic unconformities, disconformities, as well as some epirogenetic movements. Keeping in mind that to the same set of data one may attach different meanings, we were reluctant to attribute any prevailing trend to the structures governing the areal distribution of the mesozoics, in the western part of the Bavarian Basin. Contrary to that western part, the area situated East of München is characterized by well defined SE-NW striking subsurface structures: the Landshut-Neuöttinger High and the Eastern Bavarian Trough. On the West flank of the latter, the Dogger is directly overlying the crystalline Basement, the Hauterivian overlaps the Malm, the Gault rests on the Hauterivian and the Upper Eocene on the Turonian. (Ref. Anzing wells 3 and 5. TD 3'362 and 2'450 metres). Incidentally, let us notice that said Eastern Bavarian subsurface structures are parallel to the SE-NW oriented border of the present-day Bohemian crystalline Massif.

Thus, after a brief review of the various trends of the structures that controlled the mesozoic sedimentation of the Folded Jura and the subsurface of the Molasse Basin, and after examining the pre-tertiary erosional surface of the latter, it becomes apparent that the SE-NW trend is likely to be the most often encountered in that part of Central Europe, comprising Eastern Bavaria and Western Switzerland, the latter forming a large portion of the area occupied by our postulated mountain-belts and the Rawil-Doubs Graben.

6. Structural position and age of transverse-tectonics-related wrench-faults zones

— The transverse tectonics theory, enhanced by E. Parejas in Turkey (PAREJAS 1940) and by J.W. Schroeder in Iran (SCHROEDER 1944, 1945), has acquired ample support in recent years, mainly in the field of petroleum exploration.

Observed in South America, one of the facts, taken to be involved in the process of the transverse tectonics, is the existence of structures termed «Transcurrent Arches» and defined as follows:

«The transcurrent arches are old sedimentation-controlling mountain-belts, trending perpendicularly or obliquely to the general direction of the present-day orogens. They, often, consist of subsurface structures located on the extension of surface crystalline massifs» (CHENEVART 1963).

In the Eurafrican framework of the present study, many evidences go to prove that this definition applies to the North-African oil and gas-bearing subsurface highs of Arak-Hassi R'Mel, Amguid-Hassi Messaoud and Tihemboka-Edjelen (CHENEVART 1971). The definition also applies to the East Tunisian structural belt, a northern digitation of the saharian craton, bounded, to the west, by the wrench-fault zone that transects the Tunisian Atlas in a S-N direction and, to the north-east, by the offshore faults system, that stretches north-westwards between Tunisia and Sicily (Fig. 2).

— Factual observations, implications of observed tectonic and stratigraphic facts presented in the previous chapters 3, 4 and 5, point to the existence, on either side of the Rawil-Doubs Graben, of mountain-belts, which may reasonably be identified with old transcurrent arches. The characteristics, that these postulated mountain-belts share with the above mentioned typical transcurrent arches of North Africa, reinforce, by analogy, such an identification.

Actually, if we proceed by means of analogy, we notice, among other common characteristics, the present-day structural position of the truncated hercynian massifs that costitute the core of the Algerian arches (trending obliquely to the Atlas chains coeval with the Alps), the variations in time and space of the main marine transgressions, i.e. of lower cretaceous age to the south and triassic to the north (OP. CIT., Pl. 1 and Fig. 4). Likewise, the East Tunisian structural belt coincides with an old sedimentation-controlling structure, the axis of which ran, in a SE-NW direction, from Tripoli to Cap Bon (Fig. 2). In fact, south-west of this axis, the triassic stratigraphic sequence consists essentially of evaporites (mainly salt), whereas north-east of it, the Triassic displays an open-sea facies represented by a homogeneous, thick limestone sequence.

— But still more obvious seems to be the analogy between the East Tunisian transcurrent Arch and the postulated mountain-ranges bordering the Rawil-Doubs Graben, when one attempts to assess the chronology of the tectonic events that resulted in the present-day wrench-fault zones and when one compares the respective positions of such cross-strike structural features.

Thus, one of the most outstanding structure of the complex offshore faults system, that bounds to the NE the East Tunisian belt, is the rift-like depression, delineated by the faults, already shown on Staub's map, along the Tunisian Channel

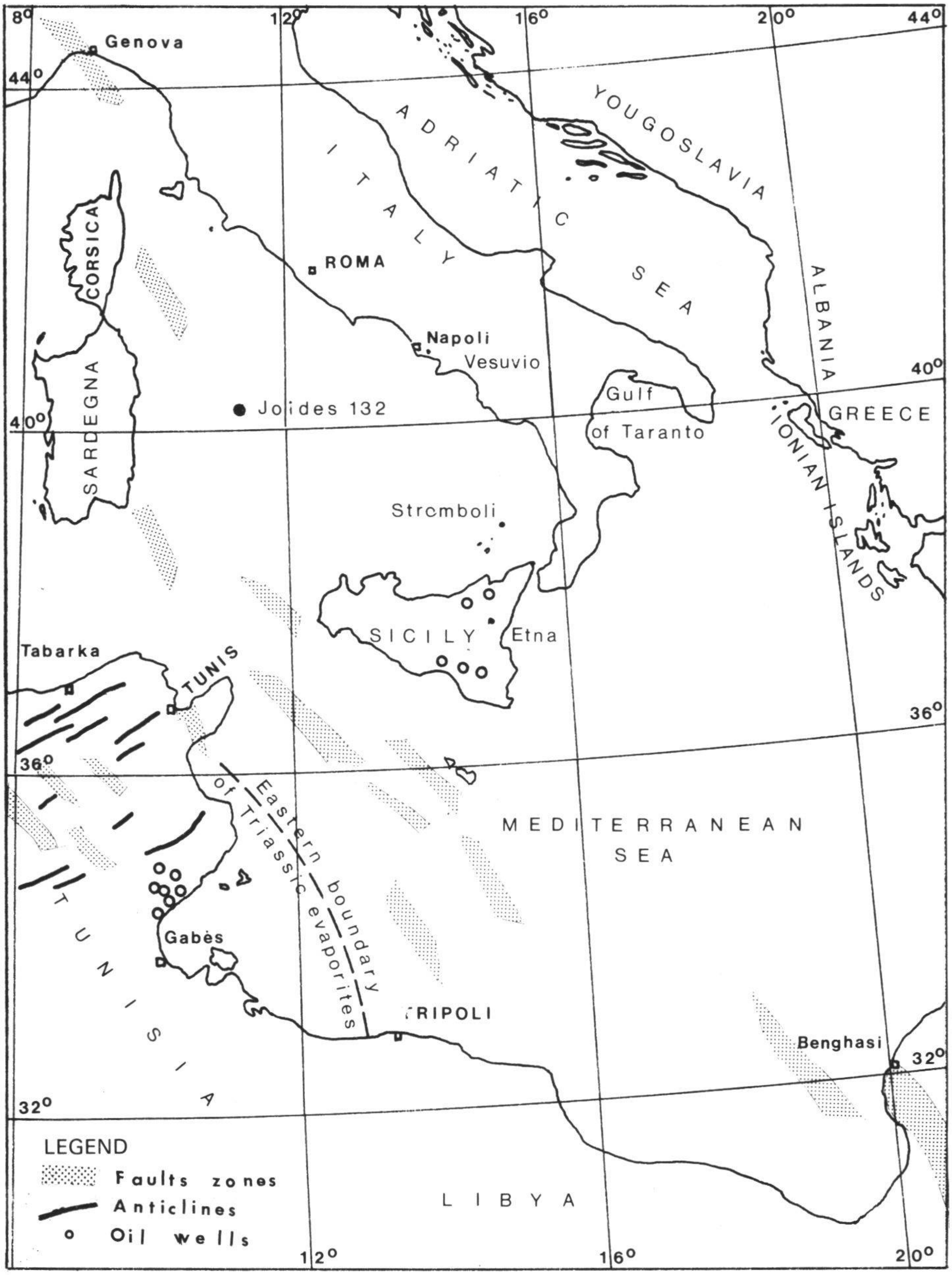

Fig. 2. The East Tunisian structural belt and its south-eastern and north-western extension.

(STAUB 1951). We may infer from the thorough works of several authors, that this depression stems from the rejuvenation of an old graben, which rejuvenation took place in relatively recent times, being coeval with the late miocene sinking of the Ionian Sea (LE PICHON, PAUTOT, AUZENDE & OLIVET 1971; GLAÇON & ROUVIER 1972; CARTER, FLANAGAN, JONES, MARCHANT, MURCHISON, REBMAN, SYLVESTER & WHITNEY 1972; BIELY, BUROLLET & LADJMI 1973; FINETTI & MORELLI 1973).

The Tunisian Channel low, or let us call it the Tunisian Graben, is 30 to 45 kilometres wide in the vicinity of Pantelleria Island and extends south-eastwards. Together with the subsidiary trenches located on its seaward side and with the intervening mid-slope platforms, the Tunisian Graben displays a seismic pattern that joins up with the Libyan Graben, an offshore and onshore, NW-SE trending feature, the southern part of which forms the north-eastern boundary of the intracratonic Syrte Basin. Thus, both the Tunisian and the Libyan Grabens are juxtaposed to the hinge line, along which tectonic movements took place, namely the late miocene sinking of the Ionian Sea and, farther SE, the kimmerian to alpine taphrogenic convulsions that gave rise to the deepening of the cretaceous and tertiary seas, from the Syrte Basin to the Cyrenaic one (BUROLLET, MAGNIER & MANDERSCHEID 1971).

The East Tunisian transcurrent Arch and the postulated mountain-ranges, which delimit the Rawil-Doubs Graben, being hercynian or older in age and being similarly bordered by grabens located along a stratigraphic hinge line (Ref. page 38), we have now, in order to complete the analogy, to define whether the age determination (late Miocene) applies also to the Pontissalian-Octodurian and to the Thunersee-Charquemont wrench-fault zones.

Even though these two roughly parallel wrench-fault zones develop steadily apart, each going its own way, they are of the same age, in the sense that the youngest observable formation, affected by both of them, is the Helvetian of the Swiss Molasse Basin. Likewise, they both result from post-orogenic convulsions since they both transect Pennine, Helvetic and Prealpine nappes in their present attitude, as well as the Franco-Swiss Folded Jura.

Hence, in addition to being located on the weakness-zones that generally constitute the passage from a mountain-belt to a graben, the Pontissalian-Octodurian and the Thunersee-Charquemont wrench-fault zones present with the faults bordering the Tunisian Graben, this further analogy to be of the same age, i.e. late miocene (to recent?).

7. Tentative structural synthesis

As a mere essay in structural synthesis, this chapter shall be confined to an overall investigation of the areal distribution of the fault-patterns recognized in Eurafrica, and to the search for their possible structural interconnetion.

— The largest part of the Pontissalian-Octodurian and Thunersee-Charquemont wrench-fault zones, delimiting the highs-bordered Rawil-Doubs Graben, is situated in the western half of Switzerland.

A better knowledge of the results of recent drillings and seismic campaigns carried out in the eastern half of Switzerland, would presumably convey information about other elongate structural sags crossing the Molasse Basin, the data acquired in the field suggesting the probable existence of, at least, one of them. Actually, this sag, we have termed Zurich fault-belt or Zurich Graben, stretches, in a SE-NW direction, from the Druesberg-Sihlsee area, along the Zurichsee and the Limmat Valley, to the north-eastern end of the folded Jura, where it joins with the important sinistral wrench-faults, that shift north-eastward the Swabian Jura mountain-ranges. In our opinion, this very likely means that our Pontissalian-Octodurian and Thunersee-Charquemont wrench-fault zones are not isolated, local structural features, but are located within a regional strain pattern and thus belong to a complex system of SE-NW trending dislocations, superimposed, because younger, to the S-N oriented faults such as, for instance, the ones expressing the Rhine Graben, or those described in the Prealps (PLANCHEREL 1979).

— From the proposition of a regional strain pattern which we advance herein, and owing to the analogy between West Europe's and North Africa's transverse tectonics, as analysed in chapter 6, there has emerged our postulate of a possible far out connection to be found in the area that extends from Aosta-Domodossola, where our initial stduy had been left off (Pl. I), down to the Tunisian offshore. The results of our preliminary field reconnaissance, combined with bibliographic data, can be summarized as follows:

From Aosta to Ivrea. About 24 kilometres East of the town of Aosta, the Dora Baltea River takes a abrupt turn and flows south-eastward along a 32 kilometres long wrench-fault zone. Lateral displacements, with the maximum lenght of slip, sudden change in the trend of morpho-tectonic units, shearing movements are best observable in the gneiss and micaschists (amphibolite lenses) of Issogne and, farther south-eastward, near the village of Donnaz. We are, here, in what has been called a «tectonic valley» or the «Aosta Valley fault» (Argand 1909).

Noteworthy is the fact that this 32 kilometres long segment of the Dora Baltea Valley (from St Vincent to Ivrea) and the Rhone Valley segment of the Pontissalian-Octodurian wrench-fault zone (from Geneva Lake to Martigny) line up remarkably well.

From Ivrea to Savona, on the northern shore of the Western Mediterranean Sea. The tectonic unit widely known as the «Ivrea body» consists of «paragneisses, mafic and ultramafic rocks» (ZINGG 1983), the emplacement of which is very likely to have occurred during the Neogene (LAUBSCHER 1970). Let us notice, however, that there are marked differences of opinion regarding this dating. Anyhow, the clear result of our rapid field reconnaissance is that the Ivrea body is transected by a bundle of SE-NW trending faults, constituing the south-eastern extension of the above mentioned «Aosta Valley fault» and, as such, continues the Rhone Valley lineament, a fact already noticed by previous authors (GUILLAUME & GUILLAUME 1982, page 265). (We shall deal with the ENE-WSW oriented Valtellina-Centovalli dislocation zones, in the next chapter, page 47).

Beyond the town of Ivrea, south-eastward, we enter a narrow zone of rolling hills, with rare exposures, and then, the flat Po Valley, where we did not carry out field work but we had some subsurface information, on which to rely, complemented by AGIP's published reports on deep wells and seismic campaigns in the Po Valley (PIERI & GROPPI 1981).

Thus, a subsurface syncline, expressed in the Miocene, can be defined between the wells S. Benigno 1 (TD 2700 m.) and Sali Vercelles 1 (TD 5806 m.), which, from the Ivrea Strambino area seems to be, for over 25 kilometres, a NW-SE trending structure, in the middle of which flows the Dora Baltea River, down to its junction with the Po River. We would not dare to precise the tectonic nature of that structure, avereaging 12 kilometres in width, since we were not in a position to define, along its borders, a continuity of aseismic zones (blind areas) that, generally, characterizes a wrench-faulting.

From the Po River to the site of AT 1 (TD 1250 m.) and AT 2 (TD 2303 m.), there is a gap in our information.

AT 1 (Asti well No 1), located about 65 kilometres SE of Ivrea, discloses a strongly disturbed Miocene (PIERI & GROPPI 1981, geological cross-section 2).

Although, the uppermost Pliocene and the Calabrian formation is quoted to be faulted (verbal communication), there is insufficient evidence, as yet, to reach firm conclusions about our postulate, between the towns of Asti and Acqui.

Such is far from being the case from Acqui to Savona, where predominantly NW-SE oriented faults transect the low mountains flanking the «Massicci di Savona» and the vast exposures of ophiolites that mark the spectacular transition from the Alps to the Ligurian Apennines. Let us call this transition zone, extending between Savona and Genova areas, the Ligurian faults belt.

From the northern shore of the Western Mediterranean Sea to the Tunisian Graben. Since about three decades, methods employing new geological and geophysical tools, includind deep sea drill on Glomar Challenger, have enabled to outline the undersea structures of the Ligurian and Tyrrhenian Seas, that part of the Western Mediterranean comprised between the Gulf of Genova, the Corsica-Sardinia Island chain and the Italian mainland.

Thus, the fault zones, shown very schematically in Figure 2, consist actually of several N-S to NW-SE elongate troughs, the main ones being, from north-west to south-east:

— the Tuscany Trough, bordered to the West by the old crystalline Massif of Corsica and, to the East, by the submarine Arch of Elba.
— The Corsica-Sardinia Trough, trending NNW-SSE, bordered, to the West by the Sardinia crystalline Massif and, to the East, by scattered highs such as the Giglio Ridge. Like the Tuscany Trough, this trough displays a horst-and-graben tectonic style. In its southern part, it branches off, in a north-west direction, towards the Sardinia Island where, from the town of Cagliari, it can be traced along the NW-SE stretching valley of Campidano.

The spatial connection between the Corsica-Sardinia Trough and the Tunisian Graben is still not fully identified, but we may reasonably assume its existence, all the more so as most authors take the two structures to be of the same age, i.e. late Miocene/Pliocene (LE PICHON, PAUTOT, AUZENDE & OLIVET 1971 et al. quoted in Stanley's review 1972). Owing to the fact that, along the inferred alignment, active volcanism still occurs (Etna, Stromboli Vesuvio), we would precise this age determination and say: late Miocene to Recent.

In brief, despite its sometimes fragmentary aspect, our information leads us to consider that the faults pattern, within which the Rawil-Doubs and the Zurich Grabens are encompassed, is, in all likelihood, kinematically linked to the North Italian and Mediterranean dislocations, down to the Tunisian and the Libyan Grabens. Hence, this faults pattern being not an isolated, local structural feature, we have now to examine what might be its relationship with the dislocations affecting its neighbouring countries of North-west Europe.

— Fault zones and Grabens stretching from Switzerland to the North Sea and farther north-eastwards. One of the most aoutstanding and best studied NW-SE oriented fault zone is the one covering a large part of the North-West European continental shelf, affecting the Vosges and Ardennes Massifs and characterized by a horst-and-graben tectonic style, between the Low Rhine - Dutch Central Grabens and the huge Groningen gas field.

At first sight, the Rawil-Doubs and Zurich Grabens seem to be unrelated to this fault zone, since the Rawil-Doubs Graben was seen to extend, probably, beyond the Bisontin Arc, towards the Morvano-Vosgian Straits (Ref. page 35). Yet, a closer look at the regional structure reveals that the NW extension of the Zurich Graben, as described on page 43, falls into line with the important SE-NW trending fault, that cuts through the Black Forest Massif, from the vicinity of the German village of Albbruck to the Rhine Graben town of Kander (a distance of about 35 kilometres).

On the other hand, the field work we undertook in sommer 1983, allows us to state that, in the crystalline Vosges Massif, the SE-NW oriented faults prevail, superimposed as they are to the S-N trending dislocations. Across either extremity of the crystalline Massif and its overlying sediments, we have mapped, among other structural features, the Mid-Vosgian fault-belt, running from the locality of Thann, north-westwards, to Bussang at the foot of the «Ballon o'Alsace», and the North-Vosgian fault - belt, which stretches north-westwards, over a distance of 120 kilometres, from Liepvre to Bouzonville (34 kilometres West of the German town of Saarbrücken). From here, all the fault - belts and other surface structures are gradually shifted north-eastwards, as a result of tectonic movements, that gave rise to the longitudinal faults mentioned in the next chapter (page 47).

The shifted structures consist mainly of a series of grabens and horsts, pertaining, as generally admitted, to a tertiary-quaternary fault-system. The best known of the grabens, on German and Dutch territories, are the Lower Rhine Graben and the Dutch Central Graben, both oriented in a SE-NW direction.

The Dutch system of grabens continues offshore into the North Sea, first in its same SE-NW direction but swings then to form the S-N trending Mid North Sea Central Graben and, farther North, the highs-and-platforms-bordered Viking Graben. Structural data on both grabens, derived mainly from the exploration of this area that has become, in the last twenty years, a proven major hydrocarbon province, have been remarkably summarized by various authors (PEGRUM, REES & NAYOLR 1975, ANDERSON 1978). According to most of them, the Central and Viking Grabens are thought to stem from a Tertiary rejuvenatian of old grabens.

The somewhat sinuous northern end of the Viking Graben, gradually passes from its S-N to a SW-NE direction. The oil producing Statfjord field, located on that structural turn, shows a strongly faulted subsurface below Norwegian waters. On the basis of scattered offshore data and of morphotectonic surveys of that part of the Norwegian coast, where structural geology controls topography, we postulate a north-eastern extension of the Viking Graben, at least as far as the Lofoten Islands.

Now, to conclude, we think that this tentative synthesis, perhaps too greatly condensed, ought to render plausible that, in their overall tectonic style and their age, the Tunisian Graben, to the South, and the Viking Graben, to the North of the studied area, do not essentially differ from the Rawil-Doubs Graben, and that the three structures share a common geological history. They constitute three of the major elements of a series of interlinked grabens and fault-belts, that form a huge tectonic line cutting across the Mediterranean, Western Europe and the North Sea. This 5800 kilometres long tectonic line figures the arc of a circle, an arcuate belt with a westwards directed convexity. For further descriptions in chapter 8, we shall call this transcontinental structural feature «the West European Fault-Crescent».

8. Differential drift of continents and presumed forces exerted to produce it

— When the West European Fault-Crescent is considered within the framework of the Northern Hemisphere, it becomes apparent that it is roughly parallel to the northern segment of the Mid-Atlantic ridges and rift-valleys (Pl. II). Furthermore, its parallelism with lineaments of continental extend is clearly brought out in land satellite images of Central and Eastern Europe (Ref. Earthnet Landsat, Paths 186 to 210 betw. Rows 12 to 37).

One of these lineaments stretches north-westwards, from the Aegean Sea to the Vardar - Skopje Valley and to the region lying between the Dinarides mountain-ranges and the Balkan orocline. It continues across the Ungarian plain north-westerly up to that part of the Danube River, located between the eastern end of the Alps and the Carpathian Mountains, then turns gradually northwards to enter the Baltic Sea, west of Gdansk-Gdynia. From there, it follows the axis of the sea and, finally swings north-eastwards to reach the vicinity of Murmansk on the Barents Sea. Of a similar arc-like shape, the other lineament runs from the Black Sea to the Lake Ladoga and to the White Sea (Pl. II). We shall call these two lineaments (ABL and BWL in Plate II) the Aegean-Baltic Seas Lineament and the Black and White Seas Lineament.

— What is the nature of these lineaments? For the time being, we are not in a position to identify the nature of the Black and White Seas Lineament. As regards the Aegean-Baltic Seas one, let us notice the complete change in the attitude of the tectonic units exposed on either side of it. The Aegean Islands, the SE-NW striking Dinarides, located on the south-west side of the lineament, display a totally different structural position than the Aegean Islands, the Balkan orocline, located on its north-east side. In the detail, the prevailing tectonic style, observed along that part of the lineament, reflects the wrench-faulting characteristics displayed along its north-western extension, where the lineament coincides with the huge sinistral strike-slip faults zone running between Alps and Carpathes, and farther north-westwards.

Moreover, late tertiary to recent volcanism appears not too far, to the East of the lineament, within a belt that extends from the Aegean Sea to the Carpathian Mountains. This fact compares with the areal distribution of the late tertiary to recent volcanic units scattered along the West European Fault-Crescent (the already mentioned Etna, Stromboli, Vesuvio active volcanoes (pages 44/45) plus the volcanic units observable on the Italian coast, between the Vesuvio and the Fiume Albegna, those of Corsica, Liguria, Hegnau, Kaiserstuhl, Vogelsberg, Westerwald, Siebengebirge).

Thus, from the facts we have tried to draw together we may reasonably infer and take as a working hypothesis that, in addition to being of a tectonic nature, the Aegean-Baltic Seas Lineament is, probably, a present-day living structural feature, as is the West European Fault-Crescent and as are, with more certainty and to a higher degree, the Mid-Atlantic ridges and rift-valleys.

— In our opinion, the question, that bears on the origin of the West European and the Aegean-Baltic Seas living linear dislocations, comes within the worldwide domain of Continental Drift. The arc-like shape of these linear dislocations, with an westwards oriented convexity, is very likely to imply a differential drift, in the sense that relative motion of fragments of the dislocation line is proportional to the intenisty of the orogenic forces, that act as driving mechanism, the strongest horizontal shear motion occurring in the westernmost part of the dislocation line.

In order to preserve clarity on the sketch map (Pl. II), we have figured, neither the transform faults (Wilson 1965) which transect the Mid-Atlantic ridges and rift-valleys, nor the longitudinal faults cutting through the Est European Fault-Crescent. Although the question as to whether the former extend into the continents is very controversial, the fact remains that, in the area initially studied, the ENE-WSW trending fault zones of Valtellina-Centovalli, Upper Rhine-Upper Rhone Valleys, south-eastern and north-western borders of the Swiss Molasse Basin, seem to play the rôle of transform faults, between which the fragments of the Crescent are westerly displaced, with decreasing intensity from the kinematic center of the arc to its extremities.

We have now to look for a force capable of disrupting the Earth's crust into such differentially moving bloks and, hence, capable of generating arcuate lines of dislocation and the ensuing differential drift of continents.

— From the «essay in geopoetry» to the most elaborate mathematical formula, the attempts to answer the question «WHAT CAUSES THE CONTINENTS TO MOVE?» have spread out into numerous variations (WEGENER 1915, HOLMES 1944, CAREY 1958, DIETZ 1961, HESS 1962, WILSON 1965, VINE 1966, LE PICHON 1968, McKENSIE 1969, MEYERHOFF and MEYERHOFF 1972, and many other authors). Not all of these authors, but a large part of them, express, despite numerous variations, their basic agreement with the theory holding that the sub-crustal convection currents are the prime cause of continental drift. If such were the case, and though the convection currents would not, necessarily, produce randomly distributed dislocations, would they generate arc-like fault-belts, parallel to one another, this parallelism rendering hardly conceivable, if not quite inconceivable any sea-floor spreading?

To get out from the impasse to which our reasoning leads, let us put the question, in other words and more explicitly, so: ARE THE CONVECTION CUR-

RENTS THE PRIME CAUSE OF THE SEA-FLOOR SPREADING, WHICH, IN TURN, CAUSES THE CONTINENTS TO MOVE, OR INVERSELY, DOES THE PRIME CAUSE CONSIST OF A FORCE THAT GENERATES, SIMULTANEOUSLY, CONVECTION CURRENTS AND CONTINENTAL DRIFT, THE SEA-FLOOR SPREADING BEING ESSENTIALLY A SECONDARY EFFECT OF IT? In order to facilitate the search for that prime cause, we have constructed an «analogic model» which, like most experimental and mathematical models, may be not quite relevant to reality because its sizes are reduced, the speed and duration of its motions amplified by several orders of magnitude, but which, nevertheless, has allowed us to reach an unexpected degree of simplification.

— Starting, on the one hand, from our working hypothesis on the nature of the Aegean-Baltic Seas Lineament and the West European Fault-Crescent (page 47), considering, on the other hand, as extremely significant the arcuate shape of these two tectonic features, roughly parallel to the Mid-Atlantic ridges and rift-valleys, we have, first, examined and tested on the «analogic model», Wegner's hypothesis, according to which continental drift could be caused by the gravitational forces. Obviously inadequate though it may have appeared in the light of Coriolis acceleration theorem, we kept experimenting the possible effects of the modelled rotation speed, which decreases from 1669 kms/hour under the present-day equator to zero at the poles. In vain!

It was only after having introduced in our experimentation a fact of global geophysics, that we were in a position to establish, that the energy able to produce continental drift, is likely to be developped NOT BY THE EARTH'S ROTATION ITSELF, BUT BY THE ACCELERATIONS AND DECELERATIONS THAT RESULT FROM THE EXISTENCE OF LONG-PERIOD IRREGULARITIES AND SEASONAL FLUCTUATIONS IN THE RATE OF THE EARTH'S ROTATION.

Mathematical supports for this fact shall now be provided:

— Figure 3 illustrates diagrammatically the long-period irregularities, as they were defined by various authors (STOKIO 1949, BROUWER 1952, VAN DEN DUNGEN, COX & MIEGHEM 1956, JONES, 1956, DANJON 1959). It also illustrates the seasonal fluctuations as they appear in the concordant results obtained by these authors.

As can be seen, the long-period irregularities appear less consistent with our viewpoint than the seasonal variations. By contrast, the latter show clearly that speed of the Earth's rotation is increasing from June to October, a fact implying a continental drift towards the West.

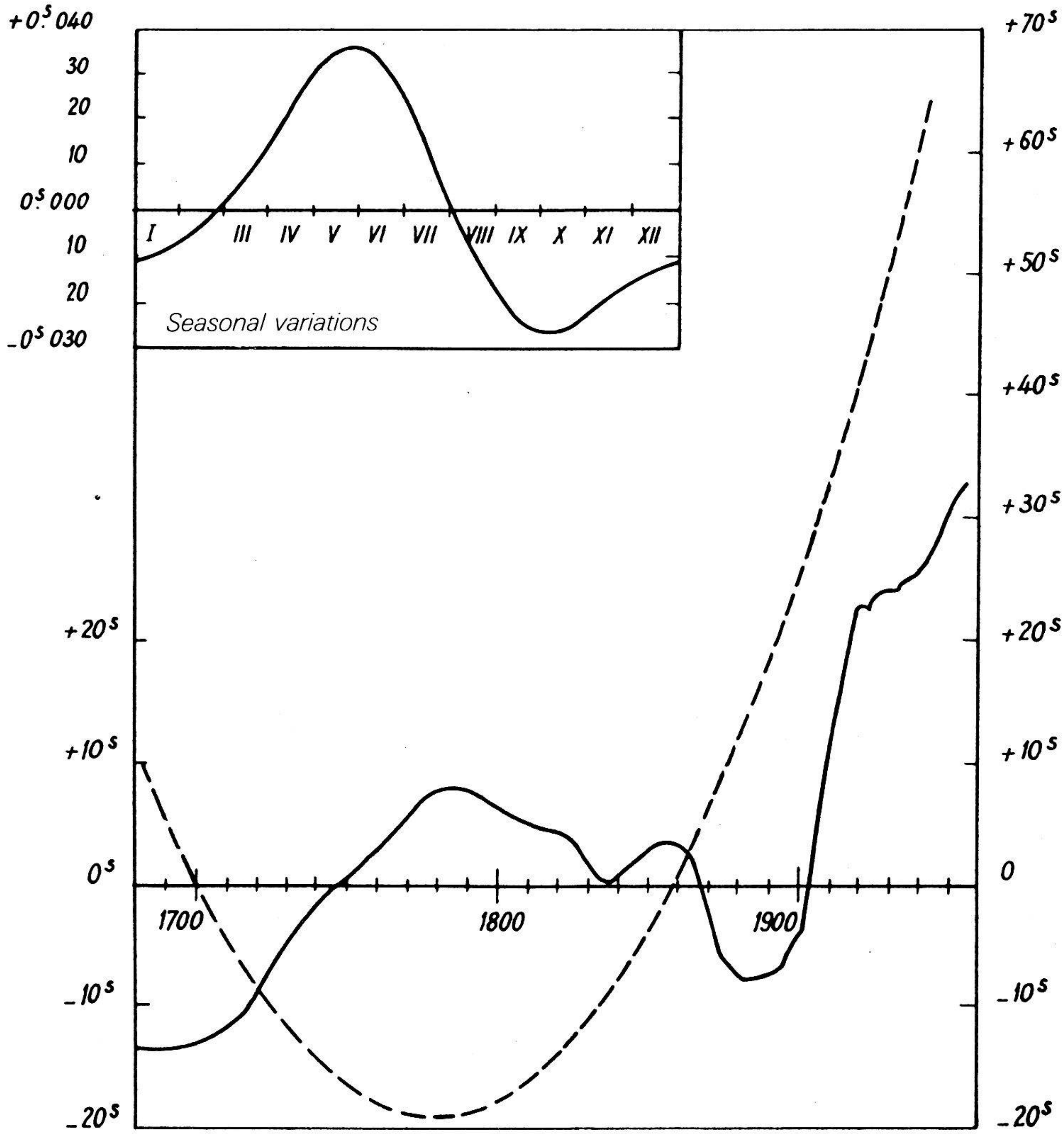

Fig. 3. Diagrams summarizing the fluctuations in the rate of the Earth's rotation. After N. STOKIO, D. BROUWER, F.H. VAN DEN DUNGEN, J.F. COX, J. VAN MIEGHEM, H.S. JONES, A. DANJON.
LEGEND: Full line = the long-periode irregularities in seconds, from 1680 to 1955.

From October to June, this speed is decreasing, but more slowly, hence a drift towards the East cannot occur, as we are going to demonstrate it.

Let us consider, as a first approximation, the effects of the variations (d) of the Earth's rotations speed (ω). The mass m, concentrated around the point P of the Earth's surface, at the latitude ϕ , will be submitted to the accelaration

$$a_A = \frac{d\omega}{dt} r \cos\phi \qquad (1)$$

towards the East

with $$d\omega = -2\pi \frac{d\tau}{\tau^2} \tag{2}$$

$d\tau$ being the variation of the daily rotation period τ of the Earth. According to Newton's law, on account of its inertia the mass m will exert the force

$$-f_A = -m\ a_A \tag{3}$$

tangential to the Earth's surface and pointing West. The force $-f_A$ is opposite to the sum f_R of the frictional forces with the Earth's surface. If f_R (assumed to be directly opposite to $-f_A$) is greater or ecual, in absolute value, to the absolute value of $-f_A$, i.e.

$$|f_R| \geqslant |-f_A| \tag{4}$$

the mass m will be affectively submitted to the acceleration a_A. But if

$$|f_R| < |-f_A| \tag{5}$$

the mass m will begin to slide toward the West and in relative motion with regard to the Earth's surface (Fig. 4).

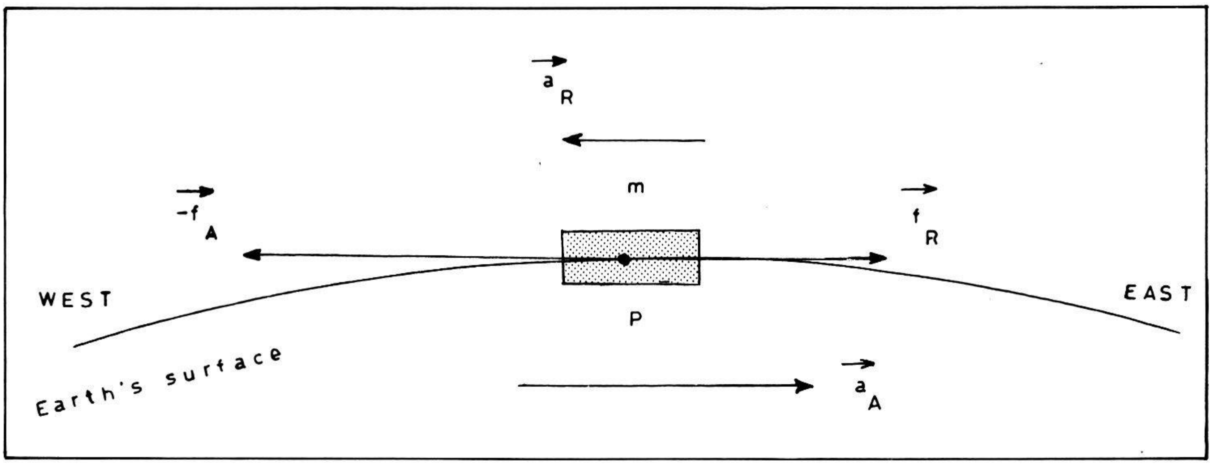

Fig. 4. Forces and accelerations brought together

With the hypothesis of a force f_R not dependant of the velocity, the relative acceleration a_R of the mass m, with regard to the Earth's surface, will be given by

$$a_R = \frac{|f_a| - |f_R|}{m} \tag{6}$$

toward the West.

The relative distance s_R covered during the time Δt (with regard to the Earth's surface) will be:

$$s_R = \frac{1}{2} a_R \overline{\Delta t}^2 \qquad (7)$$

s_R gives the drift of the mass m.

A first numerical application (for South America) leads to the following approached results:

$r = 6.3 \quad 10^6$ metres
$\Phi = -10°$
$m = 2.14 \quad 10^{21}$ Kilogrammes

From June 1 to October 1 $\Delta t = 122$ days x 86400 sec.
$d\tau = -0.060$ sec.
$a_A = 2.97 \quad 10^{-11} m/s^2$
$f_A = 6.36 \quad 10^{10}$ N

supposing $|f_A| - |f_R| = 1{,}54 \quad 10^6$ N

i.e. $|f_R| = 6{,}36 \cdot 10^{10}$ N hence: $s_R = 0.04$ metre

From October 1 to June 1 $\Delta t = 243$ days x 86400 sec.
$d\tau = +0.060$ sec.
$a_A = 1.49 \quad 10^{-11} m/s^2$
$f_A = 3.19 \quad 10^{10}$ N
$|f_R| > |f_A|$

According to (4) there is no possible drift eastward, hence $s_R = 0$

General Conclusions

To start the present work, we first resorted to geological field surveys and to reflection seismic campaigns, carried out in the narrow band that comprises the Pontissalian-Octodurian and the Thunersee-Charquemont wrench-fault zones (Pl. I), two dislocation-belts delimiting the Rawil-Doubs Graben.

Further field surveys and some complementary seismic lines, in Italy, disclosed that this narrow band was a part of the West European Fault-Crescent, a presumed living structural feature, to which a late miocene to recent age has been assigned.

The fact that the West European Fault-Crescent is parallel with two other crescent-featured, living dislocation-zones (Pl. II) gave rise to our doubts and deep perplexity about the convection currents and sea-floor spreading taken to be the cause of continental drift. Vainly we tried to conciliate facts and theory, to finally arrive at the concept of differential drift.

In our opinion, the differential drift of continents implies motions that cannot stem from deep-seated forces; whence we concluded that we had to look for a driving mechanism on the outside of the Earth's crust. The re-examination of the trapezoid configuration of aseismic zones, where the dislocations become weaker from the top to the base of the stratigraphic section (CHENEVART 1978, page 59), added further credence to our hypothesis.

The theory, we have put forth, seems also adequate to explain the sort of «stop and go» spreading rate, suggested to Ewing by the J.O.I.D.E.S. results (EWING & EWING 1959, HALLAM 1973, page 67).

Now, to answer the question contained, implicitely, in our title, on the possible significance of Eurafrican wrench-fault zones, we hold that these zones represent lines of weakness and instability of the Earth's crust, stemmed from the same stresses as those required to account for the continental drift.

We postulate that THE CONTINENTAL DRIFT IS CAUSED BY THE ACCELERATIONS AND DECELERATIONS THAT RESULT FROM THE EXISTENCE OF LONG-PERIOD IRREGULARITIES AND SEASONAL FLUCTUATIONS IN THE RATE OF THE EARTH'S ROTATION.

It might well be that the energy, thus produced, generates simultaneously convection currents. This fact, however, would not intervene in the continental drift process.

Finally, we think that, in all likelihood, the sea-floor opening and spreading are not the cause but the consequence of the drift of continents.

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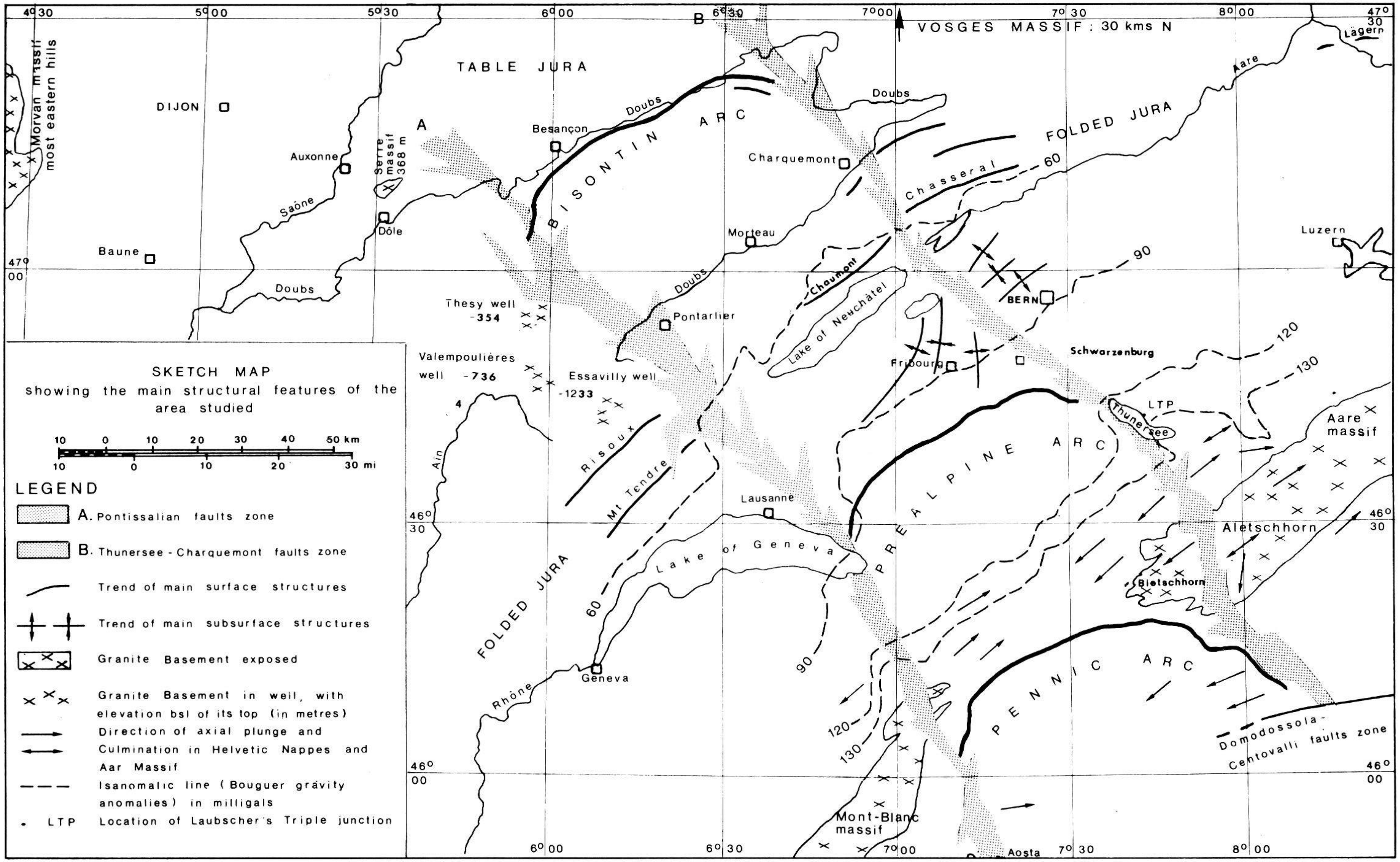
SKETCH MAP
showing the main structural features of the area studied
10 0 10 20 30 40 50 km
10 0 10 20 30 mi
LEGEND
A. Pontissalian faults zone
B. Thunersee - Charquemont faults zone
Trend of main surface structures
Trend of main subsurface structures
Granite Basement exposed
Granite Basement in well, with elevation bsl of its top (in metres)
Direction of axial plunge and Culmination in Helvetic Nappes and Aar Massif
Isanomalic line (Bouguer gravity anomalies) in milligals
. LTP Location of Laubscher's Triple junction
VOSGES MASSIF : 30 kms N
TABLE JURA
FOLDED JURA
BISONTIN ARC
PREALPINE ARC
PENNIC ARC
Morvan massif most eastern hills
DIJON
Baune
Auxonne
Saône
Serre massif 368 m
Dôle
Doubs
Besançon
Charquemont
Morteau
Pontarlier
Chasseral
Chaumont
Lake of Neuchâtel
BERN
Fribourg
Schwarzenburg
Thunersee
LTP
Luzern
Lägern
Aare
Aare massif
Aletschhorn
Bietschhorn
Domodossola-Centovalli faults zone
Thesy well -354
Valempoulières well -736
Essavilly well -1233
Ain
Risoux
Mt Tendre
Lausanne
Lake of Geneva
Geneva
Rhône
Mont-Blanc massif
Aosta
A
B
60
90
120
130
4° 30
5° 00
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6° 00
6° 30
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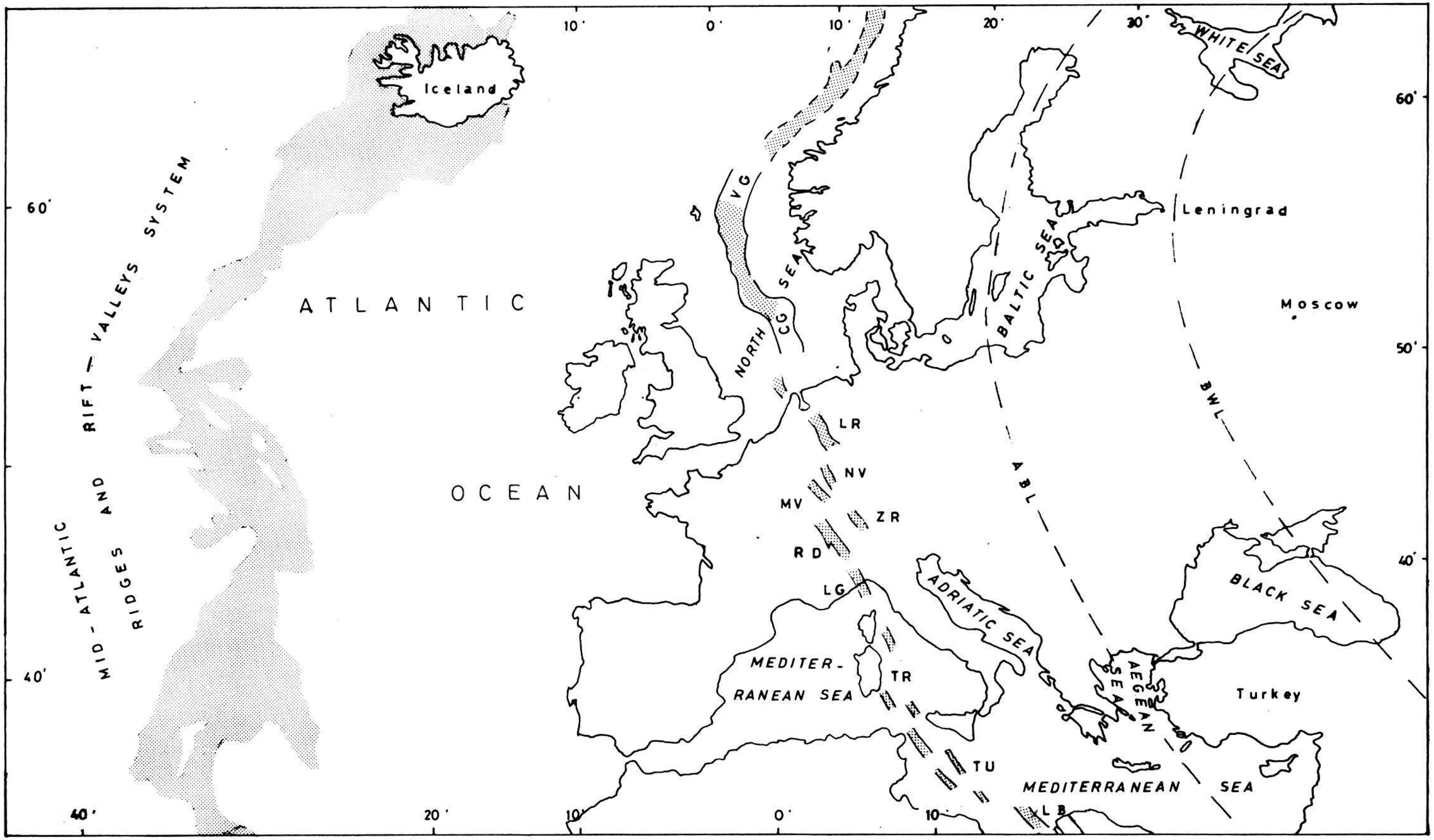
47° 00
46° 30
46° 00



Areal distribution of Eurafrican grabens, faults belts and structural lineaments roughly parallel to the northern part of the Mid-Atlantic ridges and rift-valleys. LEGEND: LB Libyan & TU Tunisian grabens, TR Tyrrhenian & LG Ligurian faults belts, RD Rawil-Doubs graben, ZR Zürich, MV Mid-Vosgian & NV North-Vosgian faults belts, LR Lower Rhine, CG Central & VG Vikings grabens. Structural lineaments ABL between Aegean & Baltic seas, BWL between Black & White seas.
To preserve clarity, transform faults are not shown.